Review

Xiantong Yu, Xin Wang, Zhao Li, Litao Zhao, Feifan Zhou, Junle Qu and Jun Song*

Spin Hall effect of light based on a surface plasmonic platform

<https://doi.org/10.1515/nanoph-2021-0217>

Received May 6, 2021; accepted August 12, 2021;

published online August 25, 2021

Abstract: In recent years, the spin Hall effect of light (SHE), also called the photonic spin Hall effect has received extensive research attention, and a series of interesting results have been achieved. This phenomenon has potential applications in nanooptics, quantum information, and optoelectronic devices. In contrast to the pure photon SHE, the photonic spin Hall effect in the surface plasmonic platform exhibits unique properties due to the surface plasmon resonance effect of noble metal material and establishes the connection between photons and electrons. Therefore, the SHE of light in a surface plasmonic platform is expected to be applied to integrated optical devices to create a novel means of developing communication devices. In this paper, we review the progress on the SHE of light based on the plasmonic platform in recent years, and we discuss the future directions of research and prospects for its applications.

Keywords: photonic spin Hall effect (PSHE); spin Hall effect of light; surface plasmon resonance (SPR).

1 Introduction

The concept of the spin Hall effect (SHE) was first established about the spin-dependent separation of electrons in a

nonmagnetic environment [1–4]. There are two crucial conditions for the occurrence of the SHE in an electron: a longitudinal applied electric field and the conversion of angular momentum [5]. In fact, photons also have spin angular momentum (SAM) and orbital angular momentum (OAM). Consequently, the research on the photonic spin Hall effect (PSHE) has also developed gradually [6, 7]. The SAM is related to circularly polarized (CP) chirality and the OAM is related to the light field gradient [8]. The spin-orbit interaction (SOI) results in an angular momentum conversion, which may lead to the spin-splitting phenomenon of light, that is, the SHE for photons. In fact, a photon as a boson is a neutral particle without a magnetic moment [9]. Thus, the direction of the spin axis of a photon cannot be changed by an applied electric field. However, because the direction of the spin axis is consistent with the light transmission, the spatial direction of a photon's spin can be changed by altering the light transmission direction [10].

Research on the SHE of light in fact predates the development of this concept. The Imbert–Fedorov effect in interfacial reflection and the optical Magnus effect in graded-index materials were studied in 1972 [11–13]. Both of these effects were later confirmed to be manifestations of the SHE of light, and they could be explained according to a fixed-phase parameter, or by the interaction between the SAM and the OAM of photons [6, 14]. In 2004, the concept of the “Spin Hall effect of light” was established by examining this phenomenon in light of the geometric Berry phase or SOI [15]. Subsequently, Bliokh et al. theoretically explained the phenomenon in a smooth, inhomogeneous, and isotropic medium with a geometric phase based on the anomalous Hall effect of electrons [16–18]. On the experimental side, quantum weak measurement technology was introduced to verify this theory [19], and this technology was a pioneering contribution to the future development of this field.

In fact, the SOI of light is weak, and the lateral shift of the SHE of light is very small in the sub-wavelength range, which makes it difficult to observe [20, 21]. Weak measurement technology is merely an indirect means of enhancing the sub-wavelength spin Hall shift and measuring it with a position-sensitive detector [19, 22, 23]. Metal nanostructures

***Corresponding author: Jun Song**, Center for Biomedical Optics and Photonics (CBOP), College of Physics and Optoelectronic Engineering, Key Laboratory of Optoelectronic Devices and Systems, Shenzhen University, Shenzhen, 518060, P.R. China, E-mail: songjun@szu.edu.cn. <https://orcid.org/0000-0002-2321-7064>

Xiantong Yu, Litao Zhao, Feifan Zhou and Junle Qu, Center for Biomedical Optics and Photonics (CBOP), College of Physics and Optoelectronic Engineering, Key Laboratory of Optoelectronic Devices and Systems, Shenzhen University, Shenzhen, 518060, P.R. China. <https://orcid.org/0000-0003-2533-3269> (X. Yu)

Xin Wang, Institute of Microscale Optoelectronics (IMO), Shenzhen University, Shenzhen, 518060, P.R. China

Zhao Li, College of Civil and Transportation Engineering, Shenzhen University, Shenzhen 518060, P.R. China

have been widely studied for the enhancement and regulation of the spin Hall shift because of their surface plasmon resonance (SPR) effect. By combining the SPR effect with SHE, the lateral shift in photon spin can be amplified, and it can be manipulated at the nanometer scale by designing a surface plasmon platform [24, 25]. This is mainly due to the special photoelectric properties generated by the surface plasmon polaritons (SPP) of metal nanostructures [26]. These properties can limit light to a local region, which is of great significance for the optical operation at the microcosmic scale [27]. In fact, SPR has spawned many branches of research, including surface-enhanced Raman spectroscopy [28–30], surface-enhanced fluorescence spectroscopy [29, 31, 32], surface-enhanced infrared spectroscopy [33–35], surface plasmon waveguides [36–38], surface plasmon-enhanced photocatalysis [39–41], and surface-enhanced energy transference [42–44]. In combination with SHE, the relevant studies have revealed new phenomena and problems that exhibit promising prospects for application [45, 46]. These new phenomena and problems are expected to provide new principles and methods for nanocharacterization and sensing technologies as well as logic and storage units for integrated optical technology [47–49].

The development of PSHE on a surface plasmon platform also has an attractive prospect for future communication technology. As a field of research in future communication technology, photon technology has long been a subject of interest [50]. The widely used electronic technology based on semiconductor materials cannot satisfy the increasingly stringent demands for high-performance communication due to the inherent physical characteristics of charging, bandwidth, and mutual interference [51]. A photon has the superiorities of low energy consumption and high speed that can be used to develop the next generation of communication technology [52, 53]. However, due to the fluctuation of light and the diffraction-limited effect, it is difficult to control a photon at the nanoscale [54]. The discovery of the SPR effect has helped overcome the diffraction limit, thus rendering optical communication at the nanoscale feasible [55, 56]. Research on the PSHE in metal structures has come to a historic juncture.

The successful combination of the PSHE with a plasmonic platform offers an attractive path for the development of plasmonic/photon SHE devices [57, 58]. Due to the flexible tunability of plasmon gratings and metasurfaces, many novel plasmonic PSHE apparatus, as well as future optical chips, have significant potential for application [59–61].

In addition, with the help of composite surface plasmon platform by introducing semiconductor materials, the

combination of photon and electron SHE can be realized, so as to achieve the purpose of controlling electron SHE, which is of great significance to the development of new optoelectronic devices [40, 41].

2 Spin Hall effect of light

When a light beam passes through an inhomogeneous medium (i.e., a refractive index gradient or anisotropic structure), photons with opposite SAMs (i.e., left and right circular polarizations) separate from one another perpendicular to the injection surface, which is the SHE of light [62, 63]. The origin of this concept is similar to the SHE of electrons, in which the refractive gradient replaces the potential energy gradient.

The study of the SHE of light can be traced back to the Imbert–Fedorov effect and the optical Magnus effect [12, 13, 64]. For the Imbert–Fedorov effect, there is a lateral displacement between the incident beam and the reflected beam at the reflecting interface. In 1955, Fedorov predicted the existence of this lateral displacement, which was verified experimentally by Imbert in 1972. It has been confirmed that the physical origin of this effect is SOI. The optical Magnus effect refers to the phenomenon in which the center of gravity of a light beam with SAM deviates laterally perpendicular to the direction of the refractive index gradient with the action of a medium refractive index gradient. In classical theory, the lateral displacements of partially reflected and refracted Gaussian beams on a plane optical interface are controlled by the law of SOI [6, 62].

After decades of development, the SHE of light has been studied on many platforms, such as metal films [65, 66], metamaterials/metasurfaces [67–69], multilayer dielectric films [70], and photonic tunneling structures [71].

Similar to the SOI of electrons, that of light refers to the interaction between its SAM and its OAM [6, 64, 72, 73]. In optical materials, the SOI of light usually leads to a SHE as well as the conversion from the SOI. The SAM is related to the ellipticity of light. The helicity of polarization σ is ± 1 for right/left-handed circular polarization (shown in the upper part of Figure 1). The two CP states refer to the two spin states of photons, $\mp \hbar$. Here, $\hbar$ is the reduced Planck's constant. Two kinds of OAM exist in the context of light propagation: an intrinsic OAM (IOAM) related to the optical vortex, and an external OAM (EOAM) related to the path of the beam (shown in middle and lower parts of Figure 1) [6]. The IOAM follows a light beam with a helical phase factor $\exp(-il\varphi)$ with a given OAM of $l\hbar$ per photon independent of the state of polarization. This l is a topological charge

and φ is the azimuthal angle in the cross-section of the beam. The EOAM is decided according to the coordinate system and the direction of motion of the light. This is considered to be similar to the angular momentum of classical particles.

The SOI between the SAM and the OAM exhibits the geometric Berry phase that leads to a series of SHE phenomena in optics [74]. The Berry phase shows that the cyclic and adiabatic evolution of quantum states can lead to a geometric phase in the parameter space. The Berry phase is dependent on the geometric properties of the Hamiltonian parameter space, which can be extended to an acyclic and nonadiabatic evolution. Based on research about the Berry phase, the corresponding optical conditions for the Berry phase in momentum space and polarization state space have been studied, corresponding to the Rytov–Vladimirskii–Berry phase and the Pancharatnam–Berry (PB) phase [8, 75, 76], respectively.

Therefore, in the laboratory coordinate system (shown in Figure 2), given a light beam propagating in the z -axis with a SAM of $\sigma \mathbf{e}_{ix}$, then the electric field polarization vector is $\mathbf{E}^\sigma \propto \mathbf{e}_{ix} + i\sigma \mathbf{e}_{iy}$. Therefore, for the case of rotation at an angle φ with the z -direction, the electric field could be written as $\mathbf{E}^{\sigma'} = \mathbf{E}^\sigma \exp(-i\sigma\varphi)$, with a geometric phase of $\Phi_G = -\sigma\varphi$ [8].

The shifts of the reflected light relative to the incident light are then obtained [6]:

$$\delta = -\frac{\sigma + \sigma'}{k} \cot \theta, \quad (1)$$

where σ and σ' refer to the helicities of the incident and reflected light, respectively. The lateral displacement δ in the above equation is also called the Imbert-Fedorov displacement.

In fact, SPR in a metal structure can produce an extra polarization-dependent phase in scattered light, which leads to the increase of the spin separation of photons [6, 20]. Studies conducted via the SPR platform have become a hotspot in research into PSHE.

3 Spin Hall effect of light in a surface plasmon platform

Noble metal materials have the characteristics of SPPs, for which a kind of surface electromagnetic wave originates from the collective oscillation of surface free electrons [77, 78]. There are two types SPPs including propagating surface plasmon polaritons (PSPPs) in metal films and localized surface plasmon polaritons (LSPPs) in specific geometry nanostructures [79, 80]. When the SPR effect occurs, the electric field near a metal surface can be significantly enhanced and the optical properties of nearby materials

Figure 1: Diagrammatic sketch of SAM and OAM [64].

Figure 2: Schematic diagram of geometric phase [6]. Reproduced with permission. Copyright 2015, Macmillan Publishers Limited, part of Springer Nature.

can be effectively controlled. The research about surface enhancement technology is based on this principle [81].

The study of PSHE based on the surface plasmon platform also uses the above two types of SPR effects. It has been found that a planar metal film structure can enhance the PSHE shift. By comparing the spin separation of the transverse magnetic (TM) and transverse electric (TE) modes, the results show that the PSHE shift of the TM mode that can excite the SPR effect increases significantly, which indicates the enhancement effect of the SPR effect on SHE. For the structure of LSPs, the interaction between light and metal structures converts the optical SAM into a surface plasmonic OAM, coupling the nanostructure geometric topological charge to the SPP field, which results in spin-separated SPP vortices [82, 83].

The plasmonic platform provides an effective method for controlling nanoscale light by the PSHE [84], and hence has important applications in nanophononics and integrated optics [85, 86]. In recent years, four main kinds of surface plasmon platforms have been used for PSHE research: metal film, nanoparticle, metasurface, and hybrid metal nanostructure. Most of these structures are polarization sensitive, and hence produce polarization-controlled surface plasmon coupling.

3.1 Thin metal film

The SHE of light produced by the reflection at the plane interface is one of the earliest studies in this field [12, 20]. It

is mainly due to the change of refractive index near the interface and leads to the coupling of SAM and OAM of light.

Due to the SPR effect, many novel optical phenomena have emerged at the noble metal films interface, especially an enhanced electric field in the nearfield. These phenomena are often used to enhance optical effects [40, 44]. In recent years, this platform has been increasingly used to study the PSHE. Some achievements have indicated that with the help of metal films, the PSHE shift can be significantly increased. These findings show that the metal film-based plasmonic platform has promising prospects [87–90].

We can describe the theoretical framework of this platform by the transfer matrix method [6, 19, 68, 91]. A Gaussian beam propagating in the z -axis with a SAM of $\sigma \mathbf{e}_{ix}$ (shown in Figure 3), then the electric field polarization vector is [92]:

$$\mathbf{E}_i = (\mathbf{e}_{ix} + i\sigma \mathbf{e}_{iy}) \frac{a}{\sqrt{2\pi}} \exp \left[-\frac{a^2(k_{ix}^2 + k_{iy}^2)}{4} \right], \quad (2)$$

where a is the Gaussian beam waist, σ is the left- and right-handed CP light beam. By introducing the transfer matrix $\mathbf{M}$, the relationship between the incident and the reflected electric field is obtained: $\mathbf{E}_r = \mathbf{M}\mathbf{E}_i$, here, $\mathbf{E}_r$ refer to the reflected electric field. Then,

$$\begin{bmatrix} \mathbf{E}_r^H \\ \mathbf{E}_r^V \end{bmatrix} = \begin{bmatrix} r_p & \frac{k_{ry} \cot \theta_i (r_p + r_s)}{k_0} \\ \frac{k_{ry} \cot \theta_i (r_p + r_s)}{k_0} & r_s \end{bmatrix} \begin{bmatrix} \mathbf{E}_i^H \\ \mathbf{E}_i^V \end{bmatrix}, \quad (3)$$

In the above formula, r_p and r_s are reflection coefficients for horizontally polarized (H) beam and vertically (V) polarized beam, respectively. k_0 is the wave. Therefore, the expressions of the reflected angular spectrum are:

$$\mathbf{E}_r^H = \frac{r_p}{\sqrt{2}} \left[\exp(+ik_{ry}\delta_r^H) \mathbf{E}_{r+} + \exp(-ik_{ry}\delta_r^H) \mathbf{E}_{r-} \right], \quad (4)$$

$$\mathbf{E}_r^V = \frac{ir_s}{\sqrt{2}} \left[-\exp(+ik_{ry}\delta_r^V) \mathbf{E}_{r+} + \exp(-ik_{ry}\delta_r^V) \mathbf{E}_{r-} \right], \quad (5)$$

So, the spin-dependent shifts,

$$\delta_r^H = \left(1 + \frac{r_s}{r_p} \right) \cot \theta_i / k_0 \text{ and } \delta_r^V = \left(1 + \frac{r_p}{r_s} \right) \cot \theta_i / k_0, \quad (6)$$

Because SPR is only excited by H polarized light, there is a large transverse beam shifts in H polarized light, which is the enhancement effect of PSHE by SPR effect. On the

Figure 3: PSHE phenomenon of light reflection on the planar film surface.

contrary, there is no shifts enhancement in the V polarized light excitation [92].

A series of achievements have been made in the study of spin-dependent enhancement using the SPR effect. The results show that because SPR is only excited by TM polarized light, there are large transverse beam shifts in TM polarized light, which is the enhancement effect of PSHE with the SPR effect. In contrast, there is no shift enhancement in the TE polarized light excitation [93].

Therefore, a glass/metal/air layered structure was studied (In Figure 4a) by Zhou et al. [93]. The results showed that the PSHE shifts of photonic crystals were much larger than had been reported previously (shown in Figure 4b) with the light incident at the SPR angle. The researchers proposed that the intrinsic physical reason for this interesting phenomenon was the sharp decrease in the reflection coefficient around the resonance angle. They also found that there was an optimal thickness at which a large shift was observed at the minimum resonant reflection (Figure 4c). These findings might establish a platform for the modulation of the PSHE, which would make possible the development of nanophotonic devices such as SPR-based sensors.

Another work by Qin et al. used the long-range SPR (LRSPR) platform for PSHE shift enhancement research by Qin et al. (Figure 5a) [94]. This study indicated that the LRSPR could significantly enhance the PSHE displacement for a fivefold enhancement value compared with what had been reported previously. They also found that under certain conditions, by adjusting the incident angle or the thickness of the silica layer or the Au layer, the direction and size of the PSHE displacements could be regulated. This study may provide guidance for the improvement of SPR sensing technology and the accurate measurement of physical and chemical parameters.

Zhang et al. studied the lateral optical force of the chiral ordering caused by PSHE in an SPR platform (Figure 5b) [95]. They found that the properties of the SPP were affected by small changes in the environmental chirality. This finding may have the potential for distinguishing the chirality of media at the macroscopic scale. In addition, it explained the interaction between the lateral force/optical torque and the chirality of nanoparticles near a surface at the microscopic scale (Figure 5c). It also proved that the introduction of chirality to the Kretschmann configuration was beneficial for the recognition of chiral enantiomers. These studies provide physical insight into the use of the SPP for chiral selectivity and provide a way to identify and separate chiral enantiomers in chemistry and biology.

Zhang et al. investigated the PSHE in a prism coupling system of magneto-optical materials and Ag/Au bimetallic films (Figure 6a and b) [91]. Compared with a single gold film, the SPR of the bimetal film had a smaller reflection coefficient, and the difference in the lateral displacement in the direction of the antimagnetic field reached $13\text{ }\mu\text{m}$ at the SPR angle. In addition, the properties of the SPR and PSHE were modulated by tuning the thicknesses of the magneto-optical layer and the bimetal film. Based on this, they proposed the enhancement of the PSHE with magneto-optical SPR for the first time.

A platform with a thin noble metal film structure obviously increases the spin Hall shift of light. The most important contribution of this platform is to improve the observability of this phenomenon, and a sensitive detection method is established directly.

3.2 Metal metasurfaces

A metasurface is a two-dimensional (2D) functional planar structure composed of many nanostructural units [92]. Due to the excellent design and ultra-thin properties of metasurface in planar structures, metasurfaces have emerged as a subject of significant research interest [96]. A metasurface structure has a simplified manufacturing process, and these structures are expected to be integrated with thin-film nanooptoelectronic devices [97–99]. Compared with the traditional interface between materials, metasurfaces exhibit the extraordinary ability to control optical flow to yield a variety of optical properties that can be used to design nanooptoelectronic devices [100]. The optical parameters of the structure of the metasurface can be flexibly controlled in design, including the material, geometry, and arrangement used.

Figure 4: a, Illustration of the PSHE in a metal/glass film with the SPR effect; b, the regulation of the PSHE shifts with the light incident angle; c, the changing of the PSHE shifts with the thickness of the metal film [93].

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At present, there are mainly two types of scatterer arrays on the metasurface platform used to support the PSHE. One type of scatterer array controls the phase of the metal scatterer by changing its geometry; the other type controls the phase change by controlling its local polarization [20].

When a light beam is incident to a metasurface, the SAM of the free space is transformed into the SPP mode with the OAM when the photon with opposite spin interacts with the SPP model, which shows the spin-dependent SPP propagation separation. This phenomenon is also known as the plasmonic SHE [24, 58, 101].

The geometry of a metasurface structure has a decisive influence on the PSHE. In real applications, a design is influenced by the relevant principles to achieve the desired purpose. For an anisotropic nanostructure, t_o and t_e refer to the complex transmission coefficients in the two principal

axes of the nanostructure. By rotating the nanostructure at an angle θ in the x-direction, the transmission coefficients can be obtained from the Jones matrix [58, 99]:

$$\begin{aligned} \mathbf{t}(\theta) &= \mathbf{R}(-\theta) \begin{pmatrix} t_o & 0 \\ 0 & t_e \end{pmatrix} \mathbf{R}(\theta) \\ &= \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} t_o & 0 \\ 0 & t_e \end{bmatrix} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}, \\ &= \begin{bmatrix} t_o \cos^2\theta + t_e \sin^2\theta & (t_o - t_e) \cos\theta \sin\theta \\ (t_o - t_e) \cos\theta \sin\theta & t_o \sin^2\theta + t_e \cos^2\theta \end{bmatrix}. \end{aligned} \quad (7)$$

$\mathbf{R}(\theta)$ is the rotation matrix.

As a CP incident light, the electric field ($\mathbf{E}_{L/R}^t$) can be acquired by the product of $\mathbf{t}(\theta)$ and Jones' vectors $\mathbf{e}_{L/R} = (\mathbf{e}_x + i\mathbf{e}_y)/\sqrt{2}$:

Figure 5: a, Illustration of the enhancement of PSHE shifts with the LRSPR structure [94]; Reproduced with permission. Copyright 2018, Elsevier. b, schematic of SPP-assisted chiral enantiomer discrimination and separation [95]; c, left, the optical torque of chiral particles with different chiral intensities; right, the schematic diagram of chiral particle motion caused by the optical force (arrow) and torques (ring) [95]. Reproduced with permission. Copyright 2019, Owner Societies.

Figure 6: (a) Illustration of PSHE in an SPR system. The magnetic field is vertical to the y-axis [91]; (b) Hz field distribution in the x-z plane at optimum thickness [91]. Reproduced with permission. Copyright 2019, Elsevier Limited.

$$\mathbf{E}_{L/R}^t = \mathbf{t}(\theta) \cdot \mathbf{e}_{L/R} = \frac{t_0 + t_e}{2} \mathbf{e}_{L/R} + \frac{t_0 - t_e}{2} e^{\pm i2\theta} \mathbf{e}_{L/R} \quad (8)$$

Subscript L/R refers to the helicity of light. $\frac{t_0 + t_e}{2} \mathbf{e}_{L/R}$ refers to the scattered light has the same polarized of the incidence light, and $\frac{t_0 - t_e}{2} e^{\pm i2\theta} \mathbf{e}_{L/R}$ refers to the scattered light

has the opposite polarized of the incidence light with an increased phase ($\pm i2\theta$). Hence, when the nanostructure rotates from 0 to π , a phase shift can be changed from 0 to 2π for the radiation along the opposite hand.

Compared with the traditional interface between materials, metasurfaces exhibit an extraordinary ability to

control optical flow to yield a variety of optical properties that can be used to design nanophotonic devices [100]. The optical parameters of the structure of a metasurface can be flexibly controlled in the design, including the material, geometry, and arrangement used.

By using a metasurface platform, Yin et al. obtained a large spin Hall shift [102]. In this process, the state of polarization was always transverse to the new direction of propagation. Due to the SOI, spin-dependent splitting was induced as the geometric polarization rotated.

A study by Shitrit et al. found that the polarization-dependent optical modes of metasurfaces appeared with the spatial reversal asymmetry [103]. The spin-splitting produced by spontaneous emission occurred due to the SOI of light, and a rule of selection was generated in spin optical metamaterials because of the symmetry constraint (Figure 7a). The reverse of the asymmetric subsurface was obtained using the pattern of the anisotropic nanostructure. This kind of metamaterial can be used to establish a platform for the application of spin-controlled nanophotons through metasurface symmetry.

The phenomena of OAM carried and transmitted by vortex light have also been investigated. This vortex light with a spiral wavefront can be limited to a 2D surface with the subwavelength as the surface plasmon vortex, which offers a way to determine unknown light-matter interaction.

Due to its extremely high rotational speed, the ultrafast dynamics of this vortex remain unexplored. By using time-resolved two-photon photoelectron microscopy, Spektor et al. demonstrated the spatiotemporal evolution of nanovortices [104]. Long-range and short-range plasmon vortices at the scale of 100 nm were observed (Figure 7b). The spatial resolution of the vortices was at the nanometer scale and the time step was subfemtosecond. Finally, the OAM order of light was directly extracted.

The SOI of light has also been the motive for the design of metasurfaces and hyper lenses. A typical example of this is the plasmon SHE, which converts the spin SAM of light into the nearfield OAM. Recently, research on the PSHE of surface plasmons in noncircular geometric metasurfaces has attracted considerable attention. By using phase-resolved nearfield microscopy, Tseses et al. experimentally demonstrated the SOI of CP light in nanostructures [105]. They revealed the topological symmetry of a hexagonal lattice and the way in which it exists in different plasmon boundary conditions. Finally, they calculated the optical force generated by the plasmonic lattice and predicted that as long as the light had the spin SAM, it could exert torque on many particles in an orderly manner. The results of this study may have applications in biology and chemistry for the simultaneous capture and control of multiple objects by light polarization.

Figure 7: PSHE in metal metasurface structures.

a, sketch map of spin-controlled surface-wave [103]; Reproduced with permission. Copyright 2013, American Association for the Advancement of Science. b, the schematic diagram of the OAM observed directly by a time-resolved two-photon photoelectron microscope [104]; Reproduced with permission. Copyright 2017, American Association for the Advancement of Science.

3.3 Metal nanoparticles

The LSPs are a form of nonpropagating excitation in metal nanostructures which is different from the PSPs of the thin film. A local field can be formed by nanostructures with omnidirectional reflection properties [106, 107]. By using a nanostructure chain, a single localized mode can be customized into a coupling mode and a hybrid local mode of the chain, and this can produce directional re-emission. Because of the geometry of the nanostructure chain, the plasmonic mode is polarized using anisotropic scattering.

At present, the most extensive research in this field involves using the interaction between metal nanoparticles to establish a mode path based on the local SPRs, and achieve a local anisotropic PSHE. Therefore, Shitrit et al. proposed and experimentally observed a localized

plasmon chain coupled with the PSHE [84]. The locally isotropic PSHE was the coupling between the SAM and the SPP OAM. They obtained the far-field distribution of the scattering spin-flip component in an ordered and disordered ring chain structure (shown in Figure 8a and b). This work is considered to have a bright future in the field of information coding and surface plasmon devices.

Recently, some progress has been made in the research of single nanoparticles. Triolo et al. proposed the nearfield spin momentum locking of local SPR [108]. These structures can limit light to nanoscale size, resulting in significant nearfield enhancement (Figure 8c). In contrast to the evanescent wave of the propagating SPP mode, the electromagnetic nearfield of the local SPR showed a certain position-dependent momentum or polarization. Near the nanoparticles, the regular momentum was rotational and tangential to the surface of the nanoparticles.

Figure 8: a, b, Far-field distribution of scattering spin-flip component in ordered and disordered ring chain structure [84]; Reproduced with permission. Copyright 2011, American Chemical Society. c, diagrammatic sketch of gold nanosphere scattering [108]; Reproduced with permission. Copyright 2017, American Chemical Society. d, SHE of scattering light from core-shell nanoparticles [109]. Reproduced with permission. Copyright 2019, Optical Society.

Normally, the PSHE of scattering light with nanoparticles is weak. It is thus a challenge to detect it directly in an experiment. Shi et al. demonstrated a broadband PSHE enhanced by core-shell nanoparticles [110]. The electromagnetism dipoles were tuned by core-shell nanostructures and excited in a timely manner in the broadband spectrum, giving rise to a strongly enhanced PSHE (Figure 8d). In addition, the interaction between the electric dipole and the electric quadrupole causes the spin Hall to move forward and backward. The far-field and nearfield numerical results verified the strong SOI. This work provides a new way to utilize the PSHE in super-resolution imaging and PSHE sensing.

3.4 Hybrid metal structure

2D materials such as graphene, monoelemental materials, and transition metal materials, have been widely studied for promising applications [109, 111, 112]. It has important prospects in the design of nanophotonic devices in the future. 2D materials have spin excitons, which is an ideal platform for the research and development of new quantum operations and storage. Because photons also have spin properties, a hybrid plasmonic platform based on 2D materials also provides a tool for the combination of spin photons and spin electrons, which is of great significance to the development of new generation communication systems.

A plasmonic platform is a new candidate strategy for the miniaturization of optoelectronic apparatuses. In recent years, research about surface plasmon platforms composed of metal materials and 2D transition metal materials has emerged [30, 40, 41, 113]. By introducing 2D transition metal materials to metal surface plasmon platform technology, full use of their optical properties can be made to assemble 2D thin-film structures with a series of characteristics and achieve the spin manipulation of photons and electrons on the same platform. This method of controlling the electron SHE is also classified as the optical SHE [14, 21], which provides a possible way to develop new optoelectronic integrated devices.

Recently, Xiao et al. investigated arbitrary spin-dependent orbits in a seamless region based on a bimetallic SPR platform by adjusting the geometric phase of the nanoblock on an Ag film with a specific hyperconfiguration of the inner and outer SPP profiles of the two spins (Figure 9a and b) [113]. In addition, by tuning the incident

polarization angle, various films were assembled. This spin-driven orbit control has potential applications in nearfield scanning microscopy, regulable plasmon apparatuses, and integrated optical elements.

With the appearance of 2D transition metal dichloride materials, research on valley excitons has flourished. By using the SAM of light, valley excitons can be detected (Figure 9c). Gong et al. demonstrated the interaction of light and valley excitons in a plasmon nanowire WS_2 layer structure [114]. The results showed that the valley pseudospin in the WS_2 was coupled with the transverse optical spin along the same direction of rotation, and the coupling efficiency was $90\% \pm 1\%$ (Figure 9d and e). This result also established a platform to regulate valley and spin information as well as to control optical accuracy at the nanoscale.

A 2D spiral plasmon structure is a general method used to induce a nearfield vortex field with an adjustable topological charge. Guo et al. demonstrated a method to explore the chiral second harmonic generation (SHG) of a single plasmonic vortex metal at a specified visible wavelength (Figure 10a and b) [82]. The metal consisted of an Al spiral slit made on an atomic-plane Al epitaxial film that enabled the accurate adjustment of the SPR. The results showed a large SHG circular dichroism. In addition, they implemented the chiral frequency-doubling conversion ability of single-layer WS_2/Al under the condition of C-exciton resonance. Because the C-exciton is not a valley exciton, the SHG enhancement in the hybrid structure came from the SPR vortex field of the Al.

4 Applications of spin Hall effect of light in a surface plasmon platform

At present, most of the work related to the PSHE based on a surface plasmonic platform focuses on the theoretical calculation and experimental measurement of the PSHE in different systems, but the related application research is relatively sparse. Nevertheless, some important breakthroughs have been made in this field, which provides valuable prospects for its potential applications. The PSHE based on an SPR platform has many special application prospects. At present, the applications in this field mainly include precision measurement, sensors, surface plasmon devices, and spin optoelectronic devices.

Figure 9: PSHE in hybrid metal structure: a, experiment sample for spin-driven orbit control. Scale bars, 4 μm [113]; b, schematics of the experimental set-up [113]; Copyright 2015, Reprinted with permission of Springer Nature Limited. c, schematics of valley-polarized exciton emission in WS₂ [114]; d, the band diagram and optical selection rules of WS₂ [114]; e, polarization emission spectrum of WS₂ without an Ag nanowire [114].

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4.1 Precision measurement

The PSHE is a powerful tool to measure the photoelectric parameters of nanostructures [115]. Examples include the thickness of a nanometal film [116], the number of layers of 2D materials, and the magneto-optical coefficient of the

magnetic film [117]. In recent years, Luo's team has studied the PSHE in the structure of nanometal films [116]. By using the weak measurement method, they observed that the PSHE can be controlled by the thickness of metal films (see Figure 11a). The measured results are in good agreement with the calculation results at the film thicknesses of 30

Figure 10: a, PSHE in Archimedes spiral structure [82]; b, chiral SHG from monolayer WS_2/Al plasmonic vortex structure [82]. Reproduced with permission. Copyright 2020, American Chemical Society.

Figure 11: a, Experimental setup [116]; b, Amplified displacements of horizontal polarized (left column) and vertical polarized (right column) beam reflection on Ag films of different thicknesses of 30 and 60 nm [116]. Reproduced with permission. Copyright 2012 American Physical Society.

and 60 nm (see Figure 11b). The PSHE can also be used to characterize the layers of graphene and other 2D materials.

Rozhkov et al. used the PSHE method to accurately determine the number of layers of graphene [118]. The experimental results are in good agreement with the calculation results, the number of graphene layers can be determined to be three which is also agreed with the result confirmed by the Raman spectra.

In addition, the results of Ren et al. showed that the PSHE is significantly different in air/magnetic systems and air/glass systems due to the different optical properties of the materials [119]. Therefore, the PSHE can be used as a tool to measure the magneto-optical constants of magnetic films, and it also has great application potential in magnetophysics.

4.2 Sensors

Biochemical sensor technology has important application value in modern scientific research. The development of sensors with high specificity, high sensitivity, and short response times has been the goal of many researchers. At present, the common biochemical sensors are semiconductor sensors, metal film sensors, and heterojunction sensors.

In recent years, some new high-performance semiconductor sensors have been widely used. For example, new 2D single element materials (Xenes) are considered promising reagents in biosensors [109, 120], bioimaging, therapeutic transmission, and therapeutics, and other new biological applications have been developed due to their

Figure 12: Plasmonic lens based on PSHE. a, b: near-field scanning images of the plasmonic lens by the irradiated of left/right-handed circularly polarized beams. c: focus distribution of the plasmonic lens. d: near field image of the plasmonic lens. e: SEM of the plasmonic lens [123]. Reproduced with permission. Copyright 2008 American Physical Society.

excellent physical, chemical, electronic, and optical properties [121, 122]. In addition, thin metal films and 2D materials sensors have shown good detection performance. These sensors have wide application prospects in molecular quantitative detection, imaging, and even biochemical reaction real-time detection based on their photoelectric characteristics and photoelectric effects.

Compared with the above spectral sensors, a new detection method has been developed based on the PSHE. First, PSHE is a sensitive physical effect. Many study results have shown that the PSHE is sensitive to the optical properties of materials [112]. The change of optical parameters at a surrounding interface has a strong influence on the PSHE displacement. In addition, the PSHE based on the surface plasma platform has obvious chiral characteristics, which makes it suitable for the chiral detection of biological and chemical molecules. In this way, the shortboard of an existing semiconductor sensor and an SPR sensor was created.

Recently, Zhang Qiang et al. proved that the chiral recognition and separation of target molecules were carried out using the PSHE of a surface plasmonic platform with numerical analysis (Figure 5) [95]. In their study, the PSHE of a surface plasmonic platform was constructed using a Kretschmann configuration. The chiral nanoparticles model was used to represent the target chiral molecules. The results showed that the characteristics of the SPR were affected by the small changes in the environmental chirality.

4.3 Surface plasmon devices

The successful combination of PSHE and metal nanostructures has provided a promising pathway for the development of surface plasmonic/photonic devices, and it has become a useful platform for design optical devices.

Spin-dependent plasmonic lenses and plasmonic couplers have proven to be feasible. In these devices, spin information can be encoded by the SPRs [8]. Due to the flexibility and tunability of plasmonic gratings, they have great potential in spin photonics and photonic circuit chips. Recent studies using the polarization-dependent splitting of metasurfaces, including focus transfer and unidirectional propagation, have enabled the use of the spin degrees of freedom in surface plasmons to achieve signal coupling and separation. The successful combination of the PSHE with plasmon nanostructures or metasurfaces has opened a path for the development of surface plasmonic devices, and this is leading to the creation of a new optical research field, namely spinoptics.

Gorodetski et al. designed a plasmonic lens based on PSHE (Figure 12) [123]. When the left-handed and right-handed CP beams irradiated the lens, the plasmonic structures with different geometric phases were focused on different locations due to the different chirality of the CP beams. For this case, the SPR platform could be used as a spin correlator. It was also demonstrated that a reversed asymmetric plasmon element might develop into a spin-dependent plasmonic coupler. Using this structure, spin information could be encoded into SPRs. Due to the flexible tunability of plasmon gratings, it has great potential for future plasmonic circuits.

4.4 Spin optoelectronic devices

The SHE was first found in electrons because of the existence of electron spin, which is the SHE of electrons in semiconductors or conductors. Because of the existence of surface plasmons, metal materials have always been a popular platform for optoelectronic research. In addition, semiconductor materials, which have developed rapidly

in recent years, can also be combined with metal materials so that spin electrons and spin photons can appear on the same platform. This opens up a possible method of studying semiconductors using the PSHE, and it establishes a connection between semiconductor spintronics and spinoptics [82].

Because the photons, electronics, spintronics, and valleytronics, have the same physical principles as SOI, the exploration of the SHE in optics can not only provide a new degree of freedom for photon control but also further promote the development of PSHE devices. The SHE in those systems is also directly analogized. Recently, researchers are committed to controlling the valley polarization in 2D materials by the SAM of photons, which has established a platform for the research of photon spin and valleytronics [8, 114].

5 Summary and outlook

The rapid development of nanotechnology and the clarification of the related basic physics have promoted research on the PSHE in plasmonic structures. The PSHE behaves as a spin-dependent transverse photon in orbital motion that maintains its angular momentum due to optical SOI. Therefore, mixed polarized light splits into two CP lights through spin correlation splitting. Similar to the electronic SHE, the PSHE has significant scientific value, and spin photonics provides a wide range of opportunities for new physics and unique applications.

Thus far, the optical SHE has been used to detect nano-displacement and to characterize nanostructures. The development of self-focusing devices based on the PSHE will continue to advance. At present, research on spin photonics has focused on the basic PSHE phenomenon in different metal nanostructures. The optical/plasmon SHE can be used to produce orbit-dependent spin Hall devices by cutting the geometry of artificial material structures, such as metamaterials or metasurfaces, and sub-wavelength nanostructures.

Hybrid metal structures combined with 2D semiconductor materials are expected to become a popular topic of research in this field. Spin valley electronics, condensed-matter physics, and high-energy physics have consistent SOI physical properties and similar theoretical bases. Therefore, the PSHE can not only provide photon control but also promote the development of photonic spin Hall devices. Considerable progress has been made in

controlling the electronic SHE in semiconductor materials by using the PSHE. Valley polarization can be controlled by light to help bridge the gap between optical spin and valleytronics.

The PSHE based on surface plasmon platforms is also facing many challenges. First, the SHE itself is a weak physical effect. It has been difficult to observe and manipulate this effect for a long time. With the introduction of weak measurement technology, a breakthrough has been made in this field. In fact, with the help of a surface plasmon platform, the PSHE has achieved considerable amplification, and some research to replace weak measurement technology has been gradually emerging. Therefore, using a surface plasmon platform to study the PSHE greatly reduces the difficulty of an experiment, and this platform is expected to continue to play an important role in the future.

Second, due to the huge ohmic loss of metal itself, the study of the metal surface plasmon effect has been greatly restricted, which will also have an impact on the use of this platform to study the PSHE. Therefore, continuously improving the performance of the platform and finding suitable surface plasmon materials and structures will be one of the focuses of this field for future research.

Finally, the fabrication of plasmonic lenses based on metasurface structures requires further development, because the geometries of metasurface structures have a decisive impact on the PSHE. Hence, the existence of defects caused by fabrication will have a significant impact on the performance of a device. In recent years, some new micro nanostructure processing technologies, such as laser processing technology and electron beam etching technology, have made continuous progress. It is believed that the continuous improvement and maturity of micro-nano processing technology will greatly promote the development of this field.

Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: This work was supported by the National Key R&D Program of China (2018YFC0910600), the National Natural Science Foundation of China (61775145/61525503/61620106016/61835009/61705143/22072094), and a project funded by the China Postdoctoral Science Foundation (2020M672762), (Key) Project of Department of Education of Guangdong Province (2016KCXTD007), the Guangdong Province Key Area R&D Program (2019B110233004), the

Shenzhen Basic Research Project (JCYJ20190808151215399/JCYJ20190808150815084).

Conflict of interest statement: The authors declare no conflict of interest.

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Supplementary Material: The online version of this article offers supplementary material (<https://doi.org/10.1515/nanoph-2021-0217>).