

Recent progress of photodetector based on carbon nanotube film and application in optoelectronic integration

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ABSTRACT

Due to its remarkable electrical and optical capabilities, optoelectronic devices based on the semiconducting single-walled carbon nanotube (s-SWCNT) have been studied extensively in the last two decades. First, s-SWCNT is a direct bandgap semiconductor with a high infrared absorption coefficient and high electron/hole mobility. In addition, as a typical one-dimensional material, there is no lattice mismatch between s-SWCNT and any substrates. Another advantage is that the optoelectronic devices of s-SWCNT can be processed at low temperatures. s-SWCNT has intriguing potential and applications in solar cells, light-emitting diodes (LEDs), photodetectors, and three-dimensional (3D) optoelectronic integration. In recent years, along with the advancement of solution purification technology, the high-purity s-SWCNTs film has laid the foundation for constructing large-area, homogenous, and high-performance optoelectronic devices. In this review, optoelectronic devices based on s-SWCNTs film and related topics are reviewed, including the preparation of high purity s-SWCNTs film, the progress of photodetectors based on the s-SWCNTs film, and challenges of s-SWCNTs film photodetectors.

KEYWORDS

carbon nanotube, high purity semiconducting single-walled carbon nanotubes (s-SWCNTs) film, photodetectors, optoelectronic integration

1 Introduction

Optoelectronic devices are essential to modern information and communication [1], display [2], optical imaging [3], and energy technologies [4]. Photodetectors, as essential optoelectronic devices, play a crucial role in industrial production, environmental monitoring, night surveillance, optical communication, remote sensing, and other emerging fields [5–7]. Shortwave infrared (SWIR) photodetectors are a type of detector that detects a wavelength range of 1–3 μm . Compared with the visible and thermal band, the SWIR wavelength band offers some unique imaging advantages with the following features and applications. First, the 1–3 μm band is the atmospheric window. This transmission rate of SWIR light in the air can reach 75% due to less absorption by water, carbon dioxide, and oxygen [8]. As a result, the SWIR detector can be utilized in harsh weather conditions such as fog or haze [9]. Second, the light spectrum in a clear night sky or full moon atmospheric glow is concentrated at 1.2 and 1.7 μm wavelengths, respectively, which means that lightweight SWIR passive detection can realize possibly at night [10]. In addition, the wavelength range of 1260–1625 nm is the low-loss region in fiber optic communication [11]. Finally, as silicon has no

effective absorption in the SWIR band, wafers and defective products can be identified at each production stage in semiconductor inspection applications [12].

Commercial SWIR detectors currently on the market are primarily constructed of III–V materials like InGaAs, which have a dynamic response range of more than 70 dB, lower dark current than germanium, and external quantum efficiency (EQE) of up to 70% [13]. But these detectors are expensive, with megapixel InGaAs detectors costing more than \$10,000, which is the main factor limiting their widespread usage. First, high quality InP substrates and high vacuum epitaxial equipment are required for high quality InGaAs crystal growth. Extend-InGaAs (cutoff wavelength exceeds 1.7 μm), which has particular applications in earth observation and space imaging, requires additional cooling equipment to reduce dark currents caused by lattice mismatch with InP substrates [14, 15]. Second, InGaAs imager only can be integrated with silicon readout circuits through flip-chip bonding due to serious lattice mismatch with the silicon substrate [16]. The complex process and low yield further increase the cost of the InGaAs camera. The development of third-generation infrared photodetectors has presented the requirements and challenges of

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small pixel size, lightweight, low power consumption, high performance, and low price (SWP3) [17], which provides new opportunities for novel low-dimensional nanomaterials such as quantum dots [18], carbon nanotubes [19], and two-dimensional (2D) materials [20]. In this review, we start from the intrinsic optoelectronic properties of semiconducting single-walled carbon nanotube (s-SWCNT), focusing on the device structure, performance, challenges of s-SWCNTs film photodetectors, and perspectives on future s-SWCNTs film SWIR detectors.

1.1 Carbon nanotube intrinsic properties

Carbon nanotubes were first discovered by Iijima in 1991 [21]. The crystal structure of SWCNTs can be seen as a result of the curling of graphene strip in a specific direction [22–24]. The energy band structure of SWCNT also has similarities with graphene [25]. A typical graphene energy band has six Dirac points overlapping the top of the conduction band and the bottom of the valence band. The energy band structure of SWCNT can be seen as the result of cutting the graphene energy band at a certain cycle length and direction. The diameter of s-SWCNT usually ranges from 0.6 to 3 nm, and the corresponding bandgap ranges from 0.2 to 1.5 eV [26, 27]. Therefore, the absorption of s-SWCNT can cover the visible to the mid-infrared band, achieving applications in broad-spectrum detection and solar cells.

As s-SWCNTs are one-dimensional semiconductors, electrons and holes form bound exciton states under the Coulomb force, with typical exciton binding energies ranging from 300 to 500 meV [22]. So the optical properties of s-SWCNT are determined by exciton [28–30], and the excitons transition follows its own selection rules [26, 31]. The selection rules for incident light polarized parallel and perpendicular to the s-SWCNT axis are shown in Fig. 1 [32]. When the polarization direction of the incident light is parallel to the axial direction of the s-SWCNT, optical absorption between subbands with the same quasi-angular momentum (E_{ii}) is allowed. While for the perpendicular polarization such transitions are forbidden and the absorption occurs at E_{ij} (between the first and second subbands as E_{12} and E_{21} transitions). The polarization response of s-SWCNTs has been investigated theoretically and experimentally [33, 34]. It should be noted that the infrared absorption coefficient of s-SWCNT can be as high as 10^5 cm^{-1} , which is one order of magnitude higher than conventional InGaAs materials [35]. Only 100 nm thick s-SWCNTs film can absorb more than 70% infrared light [36]. Such special characteristics indicate that the s-SWCNTs have a large potential in infrared detection.

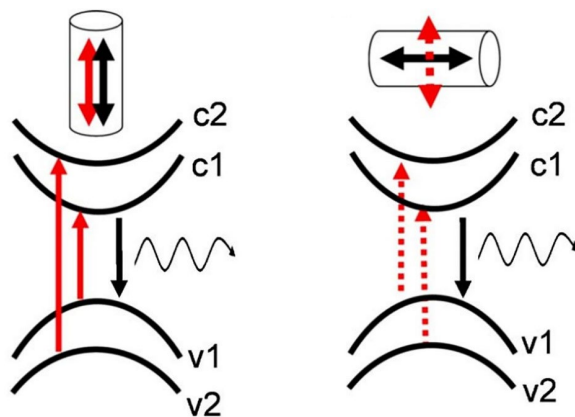


Figure 1 Schematics of optical transitions in s-SWCNTs corresponding to parallel and perpendicular absorption and emission dipoles. Reproduced with permission from Ref. [32] © The American Physical Society 2006.

1.2 Performance parameters for photodetectors

A series of key parameters to evaluate the performance of the detector are summarized in Table 1. It is worth mentioning that the requirements for photodetector metrics depend on the application area [37]. EQE represents the efficiency of the detector to convert the incident photons into the output electrical signal. Higher EQE indicates higher photoelectric conversion capability. Responsivity (R) means the responsivity of the photodetector to incident light. When the photocurrent is used as the detection signal, R corresponds to the current responsivity. Otherwise, when the photovoltage is used as the detection signal, R corresponds to the voltage responsivity. Specific detectivity (D^*) is a comprehensive performance metric that indicates the photodetector's weak light detecting capabilities. Noise equivalent power (NEP) is the minimum optical power that a photodetector can distinguish from the noise. Linear dynamic range (LDR) describes the linear response range of photodetectors, which is a significant parameter for SWIR imaging. Current noise (i_n) is an indispensable parameter for evaluating the performance of photodetectors. There are three main types of noise in photodetectors [38], the Johnson (thermal) noise (i_j), the shot noise (i_s), and the flicker noise ($i_{1/f}$), respectively. Thermal noise is generated by the irregular thermal motion of electrons and can be found in any photodetector. The carrier number fluctuation is usually the primary source of shot noise under applied bias. Flicker noise, known as the $1/f$ noise, depends on the frequency [39]. Response time is related to the rise and fall time. The rise and fall time are usually defined as the time required for the photocurrent to switch from 10% and 90% of the maximum photocurrent to 90% and 10%, respectively.

2 Types and characteristics of photodetectors

Photodetectors are categorized as bolometers, photothermopiles, photoconductors, and photodiodes based on the fundamental photoresponse mechanism. In this part, we will discuss the different kinds of s-SWCNTs detectors.

2.1 Bolometer

Bolometers are resistive elements constructed of active materials with low heat capacity and a high temperature coefficient of resistance (TCR) [40, 41]. When bolometers absorb thermal radiation, their resistance changes dramatically. The responsivity of the detectors is related to the TCR of the active material and the ambient temperature. Generally, the active material of the detector is usually suspended from isolating the ambient thermal influence. In 2006, Itkis et al. (Fig. 2(a)) reported a bolometer based on the suspended s-SWCNTs film of different thicknesses (40, 100, and 1000 nm) in a vacuum environment [35]. Under light irradiation at 940 nm with a power of 0.12 W, the responsivity of the device decreased with increasing film thickness. The voltage responsivity may reach 1000 V/W at temperatures as low as 4.2 K and the response time is approximately 50 ms. TCR of SWCNTs film can be further enhanced by reducing the thickness, increasing the purity of s-SWCNTs, and chemically modifying the s-SWCNTs. In addition to s-SWCNT as active materials [42–44], multi-walled CNT [45, 46], and s-SWCNT-polymer hybrids [43, 47] have sparked research curiosity. As a thermal detector, the detector's response waveband is not restricted by the material band gap which can detect all the infrared wavebands. Bolometers can be used for temperature sensing, industrial process monitoring, and other applications.

Table 1 Summary of performance metrics for photodetectors

Figures-of-merit	Abbreviation	Formula	Parameter	Unit
External quantum efficiency	EQE	$\frac{hcI_{ph}}{\lambda q P_{in}}$	h : Planck's constant q : elementary charge c : light speed λ : wavelength I_{ph} : photocurrent P_{in} : incident light power	%
Current responsivity	R_i	$\frac{I_{ph}}{P_{in}}$	V_{ph} : photovoltage	A/W
Voltage responsivity	R_v	$\frac{V_{ph}}{P_{in}}$	i_n : current noise A : active area	V/W
Specific detectivity	D^*	$\frac{R_i \sqrt{A}}{i_n}$	Δf : electrical bandwidth P_{max} : maximum irradiance power P_{min} : minimum irradiance power	Jones/(cm ² ·Hz ^{1/2} ·W ⁻¹)
Noise equivalent power	NEP	$\frac{\sqrt{A \Delta f}}{D^*}$	K : Boltzmann constant T : temperature	W/Hz ^{1/2}
Linear dynamic range	LDR	$20 \log \frac{P_{max}}{P_{min}}$	I_d : dark current	dB
Johnson (thermal) noise	i_j	$\sqrt{\frac{4KT \Delta f}{R_0}}$	—	A/Hz ^{1/2}
Shot noise	i_s	$\sqrt{2qI_d \Delta f}$	—	A/Hz ^{1/2}
Flick noise	$i_{1/f}$	—	—	A/Hz ^{1/2}
Response time	—	—	—	s

2.2 Photothermopile

Another form of thermal detector that has earned significant attention is the photothermopile [48–50]. The mechanism is based on the Seebeck effect. When a temperature differential between two ends of active material, thermovoltage is generated [51, 52]. Photothermopile, like bolometers, has a broad wavelength response range and can work from ultraviolet to terahertz. The thermovoltage is defined as Eq. (1)

$$\Delta V = - \int \nabla T dx \quad (1)$$

where S is the Seebeck coefficient of the active material, and ∇T is the temperature gradient in the detector channel. In 2010, St-Antoine et al. (Fig. 2(b)) developed a p-n junction on s-SWCNTs network film by K-ion doping one end of the device with an aluminum (Al) mask [53]. The difference in the Seebeck coefficient between the two ends of the device was roughly 16 V/K when the detector was tested in a vacuum room at 10⁻⁶ Torr. The detector responded to the light in the wavelength range of 500–1800 nm with a response time of 36 ms. At low frequency, the calculated detectivity was 2×10^6 Jones. In 2016, He et al. exploited a slow vacuum filtering method to prepare s-SWCNTs aligned film and fabricated photothermopiles [54]. The s-SWCNT photothermopile responds in the terahertz band with maximal 0.1 V/W responsivity and has a polarization response to polarized light. Photothermopiles can operate at zero bias voltage and room temperature. The band gap of s-SWCNTs does not restrict the response wavelength of the detector, and the performance of photothermopiles is governed by the difference in the Seebeck coefficient between the two ends of the active material. Photothermopile, on the other hand, is prone to slow response speed and low D^* , which is hard to meet the application requirements in various circumstances for fast detector response speed and high performance.

2.3 Photoconductor

Photoconductors are a type of photosensitive resistor. An exciton is created when the active material absorbs a photon with energy

higher than the active material's band gap. Then the exciton is dissociated under an applied electric field, altering the resistivity of the semiconductor. It is worth noting that impurities on the s-SWCNT have an important effect on the dissociation and binding of excitons [31, 55, 56]. In 2001, Fujiwara et al. observed the photoconductivity phenomenon on an s-SWCNT with a diameter of 1.4 nm [57]. They observed two peaks in the photoexcitation spectrum around 0.7 and 1.2 eV, corresponding to the first and second subbands of the s-SWCNT. In 2012, Lu et al. (Fig. 2(c)) developed a photoconductive detector by combining polymer poly(3-hexylthiophene) and s-SWCNTs film with the separation of exciton at the heterojunction interface [58]. At a bias voltage of 10 V, the greatest responsivity and D^* of the detector were 2.2 mA/W and 2.3×10^8 Jones, respectively. The rise and fall times of the detector were 0.6 and 1.4 ms, respectively. Compared with thermal detectors, the photoconductive detector has faster response speed and higher D^* . As the exciton binding energy of the s-SWCNTs is much larger than the room temperature thermal energy, the detector needs to operate at a large bias voltage to ensure the separation of excitons, which increases both power consumption and the dark current of the device. In 2014, Park et al. prepared phototransistors using a hybrid of s-SWCNT and C₆₀ [59]. Compared with photoconductive devices, the electrons are trapped in C₆₀ after the exciton is dissociated into free electron-hole pairs by an external electric field. By applying the bias voltage (−0.5 V) and the gate voltage (−2 V), and shortening the channel length of the device (~1 μm), the detector can achieve a gain of 2000–40,000 times and the responsivity is 97.5 A/W, with a maximum D^* of more than 10⁹ Jones.

2.4 Photodiode

In an s-SWCNT photodiode, the excitons can be separated into free carriers by the built-in electric field and finally collected by the electrodes resulting in a photovoltaic effect (Fig. 2(d)). The built-in electric field can be formed by a p-n junction or Schottky junction. Due to the existence of the built-in electric field, the detector can operate at zero bias, with low power consumption and low dark current. The photocurrent of a typical photovoltaic diode varies

linearly with a wide LDR, which is suitable for imaging applications [60]. In the following section, we will focus on the performance characteristics of different kinds of photovoltaic detectors.

2.4.1 Schottky photodiode

By changing the work function of the metal, it is easy to form Schottky diodes with varying Schottky barrier heights as s-SWCNTs are a perfect lattice semiconductor with no dangling bonds on the surface and the lack of Fermi pinning compared to traditional semiconductor material [61]. The intrinsic electric field of a Schottky photodiode originates from the contact between the metal and s-SWCNTs. In 2005, Yang et al. constructed Schottky diodes by electrostatic doping utilizing high work function palladium (Pd) and low work function Al with s-SWCNT to form p-type ohmic contacts and Schottky contacts respectively [62]. The device exhibits typical diode rectification characteristics, and the back gate voltage can further adjust the Schottky barrier of the device. However, the author does not report the optoelectronic properties of diodes. In 2010, Chen et al. designed symmetric Au-CNT-Au and asymmetric Ag-CNT-Au CNT Schottky photodiodes [63]. Photogenerated electrons and holes in symmetric field-effect transistor (FET) must tunnel through another Schottky barrier, severely limiting the photosensitivity. Both photocurrent and open-circuit voltages were significantly improved in the asymmetric Ag-CNT-Au FET based detector because electrons and holes from the Ag-CNT interface only needed to pass through a small barrier between Au and s-SWCNT before being collected, resulting in the highest open-circuit voltage (0.45 V) reported to date. The built-in field is restricted by the height of the Schottky barrier, and the dark current increased dramatically under reverse bias.

2.4.2 p-n junction photodiode

s-SWCNT photodiode also can be formed by chemical doping [64], split gates [65], barrier-free bipolar diode (BFBD), and heterojunctions [66]. In 2000, Zhou et al. used polymethyl methacrylate (PMMA) as a mask to shield one side of the channel, while potassium atoms were used to form n-doping region at half of the channel to construct a p-n junction [67, 68]. As s-SWCNTs

are perfect sp^2 lattice structures, the process of doping will degrade its electrical characteristics and introduce electron scattering centers. In 2005, Lee et al. reported a method to form p-n junction diodes along a single s-SWCNT using electrostatic doping [69]. The device exhibited excellent rectification characteristics with an ideality factor close to 1. Due to the perfect diode rectification property of this structure, band-gap renormalization and multi-exciton generation effects of s-SWCNT were also found based on this structure [70, 71]. However, due to the presence of contact barriers, the free carriers separated by the built-in field are ineffectively collected by the electrodes. The presence of barriers at the contacts and complex device structure makes it not an ideal detector structure for the application. Benefit from the development of s-SWCNTs and metal electrode research [72–77], s-SWCNTs can form p-type ohmic contacts with high work function metal like Pd and n-type ohmic contacts with low work function metal like scandium (Sc), yttrium (Y), and hafnium (Hf). In 2009, Wang et al. prepared the first BFBD photodiode using Pd/Sc aligned with the valence band/the conduction band of the s-SWCNTs respectively [78]. There is no contact barrier between the electrodes and the s-SWCNTs. The photodiode exhibited an excellent ideality factor of ~ 1.1 – 1.3 , a photovoltage of ~ 0.23 V, and a photocurrent of more than 15 nA. The BFBD device has a simple structure and operates at zero bias voltage. Therefore, the BFBD is an ideal s-SWCNT photodiode structure, which maintains the s-SWCNT's intrinsic optical and electrical properties and forms a stable photodiode.

In subsequent studies, Yang et al. achieved the photovoltage multiplication by constructing a virtual contact of Pd and Sc in the device channel [79]. The magnitude of the photovoltage increased linearly with the number of virtual contacts, and the maximum photovoltage reached 1 V. The virtual contact approach was much more straightforward compared to silicon-based or III–V compounds cascaded photodetector or solar cell, which is cascaded by heavy doping. Xu et al. explored the size reduction capability of the BFBD structure [80]. Both channel length and contact electrode sizes can be reduced to 50 nm, while diode characteristics were maintained. With a channel length of 100 nm, the ideality factor of the diode was close to 1, and the photovoltage could reach 0.24 V. The size of conventional InGaAs

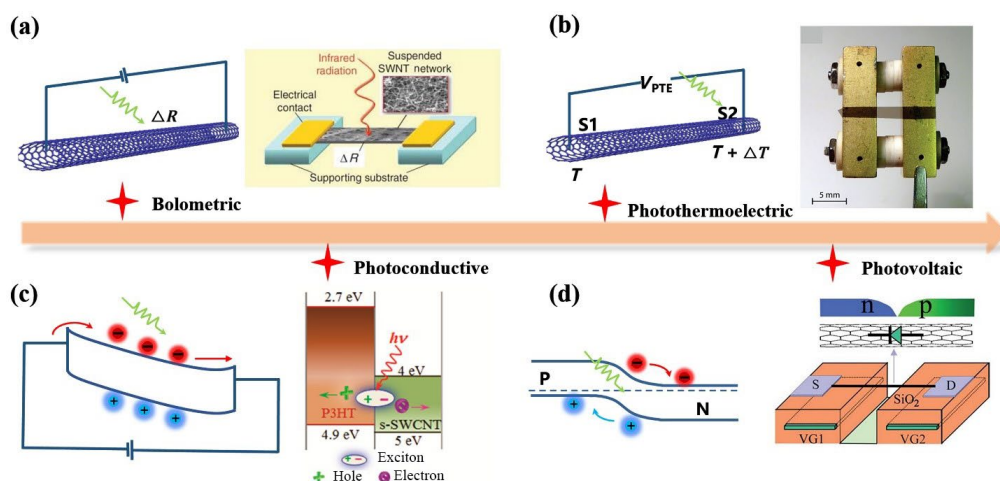


Figure 2 Mechanism and structures of four types of photodetectors. (a) Bolometric and diagram of bolometers based on suspended s-SWCNTs film. Reproduced with permission from Ref. [35], © American Association for the Advancement of Science 2006. (b) Mechanism and diagram of photothermopile consisting of a free-standing s-SWCNTs film. Reproduced with permission from Ref. [53], © American Chemical Society 2010. (c) Photoconductive detector and diagram of s-SWCNTs/P3HT nano-hybrid photoconductor. Reproduced with permission from Ref. [58], © American Chemical Society 2012. (d) Photovoltaic detector based on p-n junction diodes formed by split gates. Reproduced with permission from Ref. [69] © American Institute of Physics 2005.

photodetectors is restricted by the flip-flop process and the pixel size is usually larger than $10\ \mu\text{m} \times 10\ \mu\text{m}$. Moreover, the performance of InGaAs photodetectors has deteriorated when the pixel size is less than $10\ \mu\text{m} \times 10\ \mu\text{m}$. BFBD diodes had great potential for achieving high resolution SWIR detectors. Another experiment has demonstrated that BFBD diodes had a wide LDR of over 120 dB and the conversion efficiency can be larger than 60% in short channel diodes [81, 82]. Combined with the gold plasmonic structure, the EQE of the detector can be further improved [83, 84]. In conclusion, BFBD s-SWCNT photodetectors can be constructed by a doping-free process. The detector structure is very simple and has distinct benefits regarding device size reduction, easy integration, large LDR, fast response speed, and high conversion efficiency.

3 Purification and film preparation of s-SWCNT

Early studies have demonstrated that s-SWCNT is an ideal material for constructing the photodetector. However, due to the small absorption cross-section of a single s-SWCNT, it does not allow for high-performance photodetector with large-scale device fabrication. So large-area and homogeneous s-SWCNTs film with high purity semiconductor is crucial to bring s-SWCNTs photodetector to practical applications. In this section, we focus on the recent development of separation and purification of s-SWCNTs and the preparation of the large-area s-SWCNTs film.

3.1 s-SWCNT purification

Laser ablation [85], chemical vapor deposition (CVD) [86], arc discharge [87], high-pressure carbon monoxide disproportionation (HiPco) [88], and the Co-Mo catalyst process [89] are common methods to produce a massive amount of SWCNTs. The SWCNTs prepared by these methods were a mixture of s-SWCNTs, metallic CNTs, multi-wall CNTs, and other remaining impurities. Therefore, the separation and purification of high purity s-SWCNTs become a major challenge. Avouris et al. [90] used the electrical burn-off method to remove metallic SWCNTs in CVD-grown SWCNTs by modulating the s-SWCNTs to the off state through the gate voltage and then adding a large bias voltage to burn off the metallic SWCNTs. Zeng et al. used this method to prepare an aligned s-SWCNTs arrays BFBD photodetector with a D^* of $10^7\ \text{cm}^2\text{-Hz}^{1/2}/\text{W}$ at 785 nm wavelength [91]. The reason for the poor detector performance is that the s-SWCNTs have a lot of defects when the metallic CNTs are burned off. In addition, the burn-off method does not allow obtaining a large area of uniform s-SWCNTs film. Purification and separation of s-SWCNTs before film preparation are another more effective method, such as density gradient ultracentrifugation [92], gel electrophoresis [93], gel chromatography [94], ion-exchange chromatography [95], DNA wrapping [96–98], conjugated molecules [99, 100], etc. Due to the simplicity of the approach and the excellent selectivity of conjugated polymers, it was an effective way to improve s-SWCNTs yield and purity [101, 102]. The mechanism is to use conjugated polymers with the π - π structure to selectively wrap around the surface of s-SWCNTs through van der Waals interactions. By designing the polymer backbone, side chain structure, molecular weight, and the choice of solvent, s-SWCNTs of different diameters and chirality can be separated and purified [103]. In 2007, Nish et al. first used poly(9,9-dioctylfluorene) (PFO) to isolate and purify HiPco s-SWCNTs with diameters of

0.8–1.2 nm [104]. The photoluminescence (PL) efficiency of s-SWCNTs determines the degree of de-bundling and the isolation of individual semiconducting species. Compared to surfactant (superior sodium dodecylbenzene sulphonate), the PL efficiency of the s-SWCNTs isolated with PFO was increased more than tenfold to 1.5%. Since the diameter determines the band gap of s-SWCNTs, the separation and purification of s-SWCNTs with different diameters were necessary for different wavelength detection applications. Long alkyl chains could provide stronger bonding to s-SWCNTs and selectivity over a larger range of s-SWCNT diameters. The s-SWCNTs with diameters in the range of 0.8–1.6 nm could be separated by varying the lengths of alkyl chains (Fig. 3(a)) [105]. Jakubka et al. compared the effect of different molecular weights of PFO and poly(9,9-dioctylfluorene)-co-benzo-thiadiazole (F8BT) on the selectivity of s-SWCNTs. Using low to medium molecular weight and low concentration polymers could increase the selectivity of the s-SWCNTs. However, high molecular weight polymers with more concentrated solution are more suitable for achieving the long-term dispersion stability of s-SWCNTs [106]. Blackburn et al. demonstrated that poly[(9,9-dioctylfluorenyl-2,7-diyl)-alt-co-(6,60-[2,20-bipyridine])] (PFO-BPy) has good selectivity for s-SWCNTs with an average diameter around 1.3 nm [107]. After separation and purification, the s-SWCNT solution had no characteristic metallic SWCNTs peaks by either absorbance spectra or the Raman measurement. The purity of the s-SWCNTs was estimated to be greater than 99.0%. A succession of PFO derivatives received the same interest by changing the backbone unit. Another type of organic polymer is carbazoles-based polymers [108, 109]. The N-bridge atom in the carbazole unit tends to show sp^2 hybridization with a lone pair of electrons and a planar geometry, which enables the molecule to be more flexible and adaptive when interacting with s-SWCNTs. Gu et al. designed a polycarbazole (PCz), demonstrating excellent selectivity for s-SWCNTs of 1.5 nm average tube diameter [110]. The purity of s-SWCNTs was demonstrated to be > 99.9% by Raman spectroscopy, absorption spectroscopy, and characterization of short-channel FET devices. Subsequently, Liu et al. tested 1000 short-channel FET devices with no visible metallic SWCNTs in the CNT arrays and the estimated purity of s-SWCNTs is more than 99.9999% [111].

3.2 s-SWCNTs film preparation

After getting s-SWCNTs solution with high semiconducting purity, the next challenge is to prepare a large area and homogeneous s-SWCNTs film. Several methods such as spin coating [112], deposition [113], ultrasonic spraying [114], dip coating [115], vacuum filtration [116], and printing [117] have been demonstrated to produce s-SWCNTs network film. Deposition and dip coating methods have been widely used because of their simple operation, stability, and ability to prepare homogeneous films (shown in Fig. 3(b)). Zhou et al. immersed silicon wafers into aminopropyltriethoxysilane solution to form an amine-terminated monolayer on the wafer surface, increasing the interaction between s-SWCNTs and substrate [118]. Then, the wafer is immersed in 0.01 mg/mL of well-dispersed aqueous s-SWCNTs solution for 20 min. This solution assembly method can prepare high yield (> 98%), homogeneous s-SWCNTs film for control circuit of organic light-emitting diode (OLED) on 3-inch wafers. However, surface modification methods are time consuming and inefficient. Using organic solvent-dispersed s-SWCNTs solution, silicon wafers can be deposited with higher density film without surface modification. Tian et al. placed

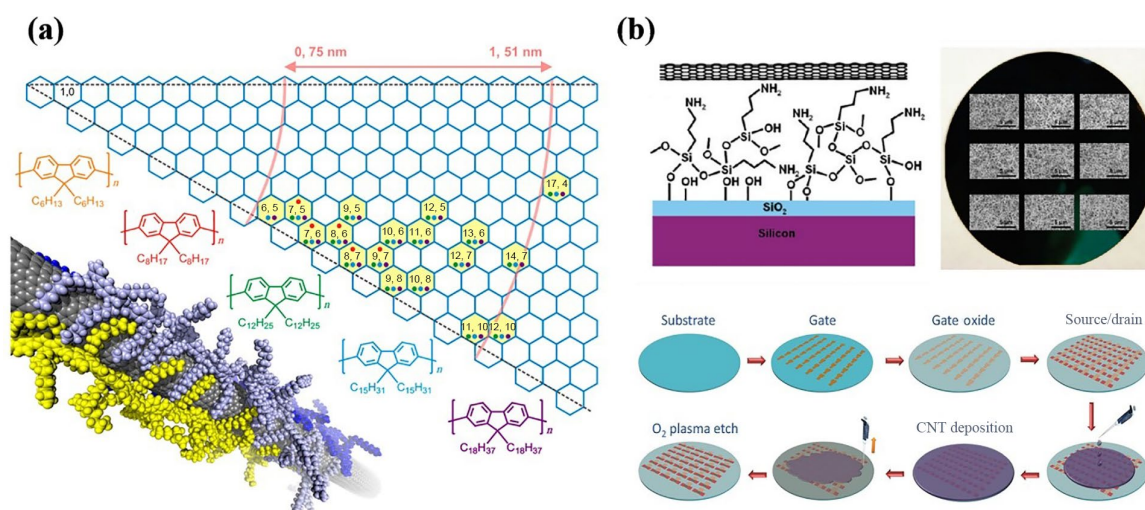


Figure 3 Purification of s-SWCNTs by conjugated polymer and preparation of films. (a) Selection of s-SWCNTs in a wide diameter range (0.8–1.6 nm) using poly-fluorine derivatives with alkyl chains of increased length. Reproduced with permission from Ref. [105], © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2013. (b) Three methods for preparing s-SWCNTs film: aminopropyltriethoxysilane (APTES) assisted deposition, organic solution deposition, and dip coating. Reproduced with permission from Ref. [118], © American Chemical Society 2009. Reproduced with permission from Ref [119], © Tian, B. Y. et al. 2016.

substrates (silicon wafers, glass, or polyethylene terephthalate (PET)) in a culture plate and then dripped only 3 mL of s-SWCNTs solution onto the substrate surface by pipette [119]. Finally, the substrate was dried in a nitrogen atmosphere to obtain a large homogeneous s-SWCNTs film. 25,200 devices were prepared on a 4-inch silicon wafer with almost 100% device yield. The dip coating is a method for creating s-SWCNTs film by continually pulling the substrate in and out of the solution [120]. Liang et al. prepared homogeneous s-SWCNTs film with controlled density on a 4-inch wafer and a 370 mm × 470 mm glass substrate by varying the number of lifts and lifting speed in a dispersed s-SWCNTs organic solvent [121]. The dip coating is a density-controlled, efficient, and large-scale method for s-SWCNTs films.

4 s-SWCNTs film photovoltaic photodetector

In the past decade, the increasing maturity of the separation and purification technology of s-SWCNTs and film preparation technology has constructed the foundation for the practical application of s-SWCNTs. Photovoltaic photodetectors have the characteristics of a simple device structure with low power consumption and dark current. In this section, photovoltaic photodetectors based on s-SWCNTs film are discussed, containing Schottky junction, heterojunction, and BFBD structures.

4.1 Schottky junction photodetector

In 2012, An et al. prepared a vertical structure of s-SWCNTs/p-type silicon Schottky photodetector by depositing a ~ 50 nm thick s-SWCNTs film on a p-type silicon substrate (shown in Fig. 4(a)) [122]. In this structure, the s-SWCNTs film acted as the transparent electrode, and silicon acted as the active semiconductor layer. The Schottky barrier height between s-SWCNTs and p-type silicon was 0.4 eV. Optoelectronic characterization of the detector shows that the EQE of the device was 10%–15% in the wavelength range of 400–1000 nm. The photodetector responsivity reached a maximum of 0.1 A/W at 840 nm. Current noise spectral density demonstrates that the photodetector was dominated by 1/f noise at reverse bias, and the

noise current increases with increasing reverse bias voltage. The D^* and NEP of the detector were 1.1×10^8 Jones and 1.4×10^{-10} W at 1 V bias, respectively. A large number of defects and traps are introduced at the interface between the s-SWCNTs film and the silicon surface during the s-SWCNTs film deposition process and it also leads to an uneven natural oxide layer on the silicon surface. The detector had a considerable time constant with a response time of 15 ms. Because the active layer of the photodetector was silicon, its response band covered the whole spectrum of visible light and the same device structure is also applicable to solar cells [123].

In 2015, Wang et al. designed and fabricated a vertical structure s-SWCNTs/n-type silicon photovoltaic solar cell and used MoO_x as an interface layer between the s-SWCNTs film and silicon (shown in Fig. 4(b)) [124]. The MoO_x interface layer acted as both a reflection reduction layer and a hole transport layer, reducing the Schottky barrier and increasing the light absorption of silicon and carrier collection efficiency. The EQE of the device could reach 17%. In 2016, Zhang et al. designed Schottky photodetectors with a single layer of graphene and s-SWCNTs film (shown in Fig. 4(c)), where the s-SWCNTs film acted as the active layer [125]. The detector showed a fast response, with the rise time and fall time being 68 and 78 μs, respectively, due to the high quality Schottky junction formed by the clean interface of graphene and s-SWCNTs film. In addition, the detector exhibited an excellent dynamic response with an LDR of 58.8 dB. In 2018, Cao et al. prepared s-SWCNTs film by dip coating and constructed graphene/s-SWCNTs film Schottky photodiodes array (shown in Fig. 4(d)) [126]. The wavelength response of the photodetector was 500–1400 nm, and the peak responsivity at 532 nm was 78 A/W. The photodetector also had a fast response time of 80 μs at 1 V bias. When s-SWCNTs were used as the active material, their intrinsic photoelectric properties were maintained. However, in the Schottky junction photodetector, to improve the efficiency and speed of exciton separation, the device tended to operate at a certain bias voltage, which led to a large dark current. In addition, the number of defects at the Schottky junction interface is an essential factor affecting the performance of the device. Defects at the interface will capture photogenerated carriers and reduce the responsivity and D^* of the photodetector.

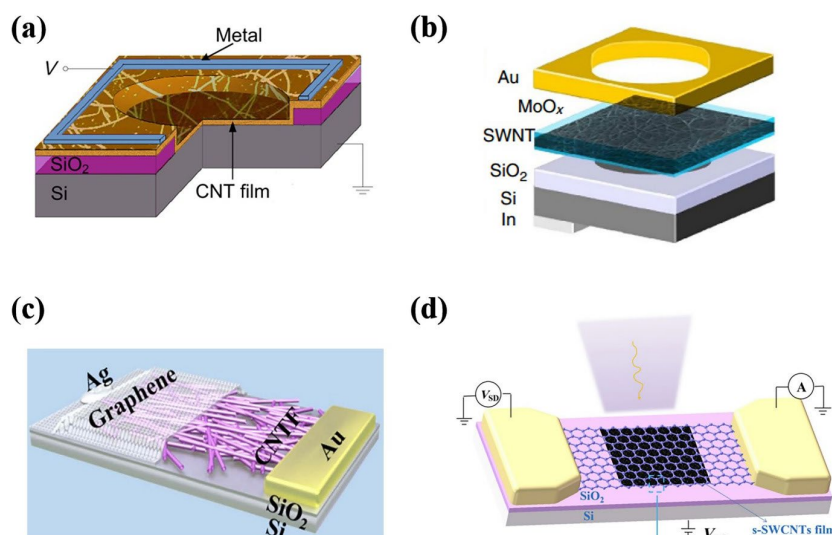


Figure 4 s-SWCNTs film Schottky junction photodetector and solar cell. (a) s-SWCNT film/p-type silicon Schottky photodetector with vertical structure. Reproduced with permission from Ref. [122], © American Vacuum Society 2012. (b) P-SWCNTs film/n-type silicon photovoltaic solar cell. Reproduced with permission from Ref. [124], © Macmillan Publishers Limited 2015. (c) and (d) Graphene/s-SWCNTs film Schottky junction photodetector. Reproduced with permission from Ref. [125], © Zhang, T. F. et al. 2016. Reproduced with permission from Ref. [126], © Cao, J. et al. 2018.

4.2 Heterojunction photodetector

Another kind of photovoltaic detector is the s-SWCNTs film heterojunction photodetector, which is constructed of s-SWCNTs and another semiconductor with matching lattice properties but different band gaps [127]. The photogenerated excitons diffuse to the heterojunction interface and are dissociated into free carriers under the built-in electric field, with the hole-transporting as the donor material and the electron-transporting as the acceptor material. Photodetectors based on s-SWCNTs/polymer heterojunction have been successfully implemented by many groups, where s-SWCNTs film is used as the donor material.

In 2009, Arnold et al. first used HiPco s-SWCNTs wrapped by poly[2-methoxy-5-(3',7'-dimethyloctyloxy)-1,4-phenylenevinylene] (MDMO-PPV), 0.7–1.1 nm diameter HiPco s-SWCNTs, and C₆₀ to form type-II heterojunctions (shown in Fig. 5(a)) [128]. The peak EQE of the detector at 1155 nm was 2.3% with a responsivity of 12 mA/W and a broad spectral response (400–1450 nm). The detector could operate at zero bias, and the D^* exceeded 10^{10} Jones in the wavelength range of 400–1450 nm with 7.2 ns response time. But there were some drawbacks, such as the cut-off wavelength of the detector was 1450 nm due to the band gap of s-SWCNTs. The poor coupling between the wrapped s-SWCNTs also results in a diffusion length of exciton less than 3 nm. When the thickness of the MDMO-PPV/s-SWCNTs layer was thicker than 15 nm, the EQE of the detector did not further increase.

In 2010, Bindl et al. used higher purity s-SWCNTs film purified by PFO, and C₆₀ to form a heterojunction detector (shown in Fig. 5(b)) [129] in which the diameter of s-SWCNTs was less than 1 nm. Due to the optimized thickness of the s-SWCNTs and energy band matching, the peak EQE of the detector at 1205 nm was 12.9%, with a D^* of 6×10^{12} Jones. This research group further optimized the purification method, then heterojunction photodetectors were constructed by (7, 5) chiral enriched s-SWCNTs with C₆₀ [130]. The peak EQE and energy conversion efficiency of the 1055 nm device were 34% and 7.1%, respectively. The s-SWCNTs/C₆₀ heterojunction detector exhibited high EQE

and fast response speed by optimizing the semiconductor purity and surface polymer of the s-SWCNTs. However, to match the C₆₀ energy band, the diameter of s-SWCNTs needs to be less than 1 nm, which limits the cut-off wavelength of the photodetector in SWIR. It is expected that choosing s-SWCNTs with a larger diameter will extend the wavelength of the photodetector to 2000 nm, but further exploration is needed to find materials that can match the band gap of the s-SWCNTs with a larger diameter.

Another photodetector is the s-SWCNTs film heterojunction phototransistor. The s-SWCNTs phototransistor typically has a very high gain by integrating an extra transportation layer with high carrier mobility [131]. The photogating effect generated by proper band alignment between functional materials may dramatically increase carrier lifetime. Thus, hybrid phototransistors have significantly improved photoresponse than other types of photoconductors, but the cost is slow response speed of the detector [132]. In these hybrid phototransistors, s-SWCNTs film is used as transport layer with high mobility. Quantum dots, perovskites, and 2D materials are usually used as absorbance materials.

In 2018, Yang et al. fabricated photoinduced memory heterojunctions of MoS₂/s-SWCNTs (shown in Fig. 5(c)) [133]. Due to the high gain under 532 nm light, the heterojunctions exhibited a responsivity of up to 8×10^3 A/W and an impressive D^* of 10^{16} Jones. In 2021, Liu et al. also fabricated a quasi-2D perovskite/s-SWCNTs heterojunction (shown in Fig. 5(d)) [134]. The gain of the phototransistor was up to 4.1×10^6 under 598 nm wavelength light irradiation. The responsivity and D^* of the phototransistor were 2×10^6 A/W and 7×10^{14} Jones, respectively. Although such phototransistors often exhibit high gain and D^* . In comparison, the response time of the phototransistor is typically between milliseconds and seconds. The operating wavelength of the phototransistor is determined by the absorbance material and s-SWCNTs film only plays the role of FET channel in this structure [135, 136]. Some progress has also been made in the study of s-SWCNTs and multi-wall CNTs for photomechanical detection [137, 138].

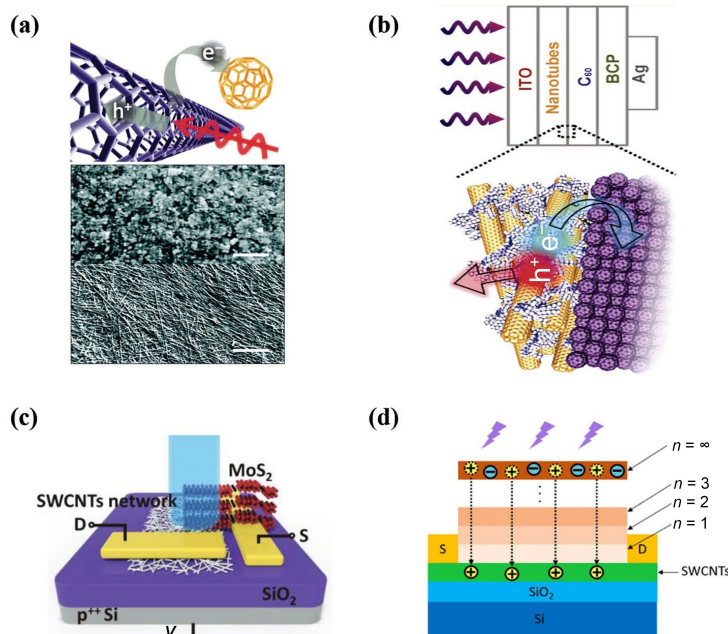


Figure 5 s-SWCNTs film heterojunction photodetector. (a) and (b) Structure and mechanism of s-SWCNTs film/heterojunction photodetector (scale bar in (a) = 500 nm). Reproduced with permission from Ref. [128], © American Chemical Society 2009. Reproduced with permission from Ref. [129], © American Chemical Society 2010. (c) MoS₂/s-SWCNTs film heterojunction phototransistor. Reproduced with permission from Ref. [133], © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2018. (d) Quasi-2D perovskite/s-SWCNTs film heterojunction phototransistor. Reproduced with permission from Ref. [134], © Wiley-VCH GmbH 2020.

4.3 BFBD photodetector based s-SWCNTs film

The first BFBD photodetector with high purity s-SWCNTs film was prepared by Liu et al. [139]. Due to the limitation of s-SWCNTs purity ~ 99.9%, a small number of metallic SWCNTs were present in the channel of the device. The optoelectronic properties were dominated by the Schottky junctions of the disordered metallic and s-SWCNTs in the channel. The average diameter and length of SWCNTs were 1.3 nm and 1 μ m, respectively. This work also compared the transport and photovoltaic properties of BFBD detectors fabricated from s-SWCNTs film with the purity of 99%, 99.9%, and > 99.9%. For s-SWCNTs film with 99% purity, the detector had higher current density and lower on/off ratio due to metallic SWCNTs in the channel. When the channel length was 0.4 μ m, the photovoltage of the detector was only 10 mV, which was much smaller than the result on a single s-SWCNT. While the channel length was increased to 2 μ m, the photovoltage increased up to 23 mV. The photovoltage of 99.9% purity of s-SWCNTs film can reach 147 mV, and the maximum photovoltage is 260 mV for purity of s-SWCNTs greater than 99.9%. These findings demonstrated that the semiconductor purity of the s-SWCNTs film was crucial to the performance of the BFBD photodetector. When metallic SWCNTs connected the two electrodes directly, the photodetector did not exhibit the obvious photovoltaic effect due to the large leakage current. Actually, the magnitude of the electric field built-in electric field of the photodetector was determined by the band gap of the s-SWCNTs.

In 2016, Liu et al. developed high purity s-SWCNTs film (> 99.9%) via deposition and thoroughly investigated its optoelectronic properties [140]. Figure 6(a) shows the structure of the photodetector. The photodetector exhibited good diode properties, with an ideality factor of 1.83. When the optical power density was 210 W/cm², the photocurrent and photovoltage of the detector were 1.97 nA and 225 mV, respectively. The

photocurrent varies linearly as the incident optical power density increases, but the photovoltage changes logarithmically. To get a higher photovoltage and increase the signal-to-noise ratio of the photodetector, they cascade the virtual contacts in the channel of detector and the photovoltage increases efficiently. Under 1800 nm illumination, the photovoltage of the BFBD photodetector grew linearly with the number of cascades. The photovoltage of the tenfold cell could reach 2.12 V. The noise of the photovoltaic detector consisted mainly of thermal noise, shot noise, and flicker noise. Detector noise was dominated by thermal noise, which had a noise density of 1.14 μ V·Hz^{-1/2} while operating in zero bias. When the device was operated at reverse bias voltage, the noise current density displayed typical 1/f characteristics, and the noise of the detector was dominated by 1/f and shot noise. The detector had an excellent response in the 1200–2100 nm band. The tenfold cell detector peak voltage responsivity and D^* could reach 1.5×10^8 V/W and 1.25×10^{11} Jones, respectively, at room temperature.

To demonstrate the detector's suitability for usage in harsh conditions, researchers exposed it to a laser beam with a power density of 100,000 W/cm². The results showed that s-SWCNTs film BFBD detectors have a significant promise for SWIR detection applications. However, many s-SWCNTs inter-tube connections existed in the cascaded device channel, and the detector had a large series resistance. The response time of the detector was larger than 10 ms.

The linear photocurrent signal was more suitable for back-end circuit processing. Although s-SWCNTs had an SWIR absorption coefficient as high as 3×10^5 cm⁻¹, the BFBD current responsivity was restricted to ~ 1 mA/W, as the absorption restriction (< 2%) of single-layer network s-SWCNTs film with low density, which limited its practical applicability. In 2017, Huang et al. designed a BFBD s-SWCNTs film detector with plasmonic enhancement to overcome this critical problem [141]. The absorption of incident light by the s-SWCNTs film was amplified by an axe-like structure

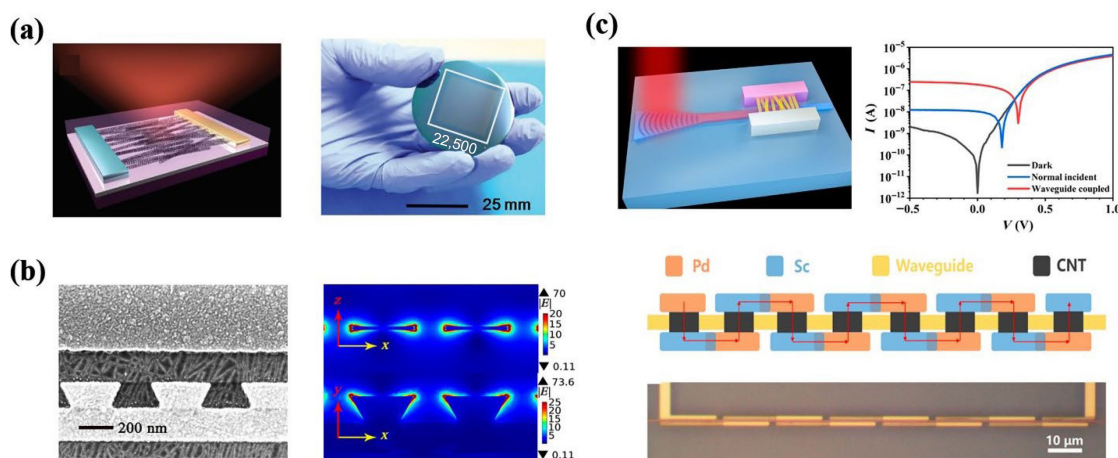


Figure 6 s-SWCNTs film BFBD photodetector. (a) Schematic of asymmetrically contacted s-SWCNTs film photodetector. Reproduced with permission from Ref. [140], © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2015. (b) Plasmonic enhanced s-SWCNTs film BFBD photodetector. Reproduced with permission from Ref. [141], © American Chemical Society 2017. (c) Silicon-waveguide-integrated s-SWCNTs film BFBD photodetector and virtual contacts structure. Reproduced with permission from Ref. [142], © American Chemical Society 2020.

of periodic plasmonic electrodes (shown in Fig. 6(b)), which were designed to resonate at a wavelength close to 1670 nm. The photocurrent of the detector was linearly proportional to the power density variation. When the channel length was 500 nm, the photocurrent responsivity of the plasmonic enhanced detector reached 7.9 mA/W as compared to the normal BFBD detector structure with a current responsivity of 0.93 mA/W under 1650 nm wavelength light irradiation. The noise power spectrum demonstrated the plasmonic structure did not introduce any additional noise. The peak D^* is 1.46×10^8 Jones, which was 11.4 times than normal BFBD photodetector.

In 2020, Ma et al. integrated s-SWCNTs film BFBD detector (shown in Fig. 6(c)) with a silicon waveguide in which the optical transmission direction was perpendicular to the direction of carrier transport [142]. Although the absorption layer of s-SWCNTs film was relatively low for normal incident light, the strong coupling between the waveguide and s-SWCNTs film allowed for great responsivity and fast response speed. Through the simulated design of waveguide and optical grating size, the current responsivity of a BFBD detector based on a waveguide is 12.5 mA/W. The virtual contacts were distributed on both sides of the waveguide to multiply the photovoltage that could reach 1.49 V at 14.9 μW optical power. The waveguide-integrated BFBD detector not only substantially improved the current responsivity of the BFBD photodetector but also exhibited the potential of s-SWCNTs in monolithic optoelectronic integration.

Integrating optical microstructure and BFBD detector can significantly improve the photocurrent responsivity of the photodetector. However, the optical microstructure has some limitations. First, the absorption enhancement for specific wavelengths necessitates a particular structure, which cannot achieve a broad-spectrum response. Furthermore, the photocurrent responsivity based on the optimized BFBD photodetector is about 10 mA/W, which is still two orders of magnitude lower than the traditional SWIR detector (0.7–1 A/W).

The primary reason for the BFBD detector limited photocurrent responsivity is the absorption restriction (< 2%) of single layer network s-SWCNTs film. As a result, another strategy is to raise the thickness of the s-SWCNTs film to improve its absorption. However, increasing the thickness of the s-SWCNTs film in BFBD structures also brings some new challenges. First, the

high purity s-SWCNTs film is purified by polymers such as PCz. Because of the poor coupling in the wrapped s-SWCNTs, the exciton diffusion between s-SWCNTs is just 3 nm. Furthermore, because the built-in electric field of the detector is near the contact electrode, photoexcitons that cannot diffuse to the built-in electric field do not contribute to the photocurrent effectively. In addition, if there is no polymer on the s-SWCNTs surface, the ohmic contact can be achieved by adjusting the work function of the metal. But the wrapped polymer on s-SWCNTs will introduce a potential barrier between the n-type electrode and the s-SWCNTs, affecting the separation of exciton and the collection of free carriers. Finally, the modeling findings reveal that s-SWCNTs have an electrostatic shielding effect for multilayer s-SWCNT films. In the multilayer s-SWCNT films, the Schottky barrier between contact electrodes and s-SWCNTs will increase when s-SWCNTs far away from the contact electrode [143]. Therefore, the s-SWCNT films and device structure need to be further optimized to improve the detector performance.

5 s-SWCNTs film BFBD photodetector optimization

5.1 s-SWCNTs film optimization

As previously mentioned, using conjugated polymer separation and purification s-SWCNTs is the most effective method up to date to achieve the high-purity, large-area, and homogeneous s-SWCNTs film. However, the residual polymers are often present in the prepared s-SWCNTs films. It will affect the inter-tube carrier transport and the exciton diffusion in the channel, introducing Schottky barriers at the contact interface between electrodes and s-SWCNTs, increasing the contact resistance of the device, and decreasing the collection efficiency of photogenerated carriers. Therefore, how to remove polymers on s-SWCNTs film surface becomes a challenge to improve the performance of optoelectronic devices.

There are two primary ways to remove polymer from the surface of s-SWCNTs. One method is to remove polymer from the s-SWCNTs solution. In 2016, Lei et al. made polymer containing imine bonds decomposing into monomers by lowering the potential of hydrogen (PH) of the solution (shown in Fig. 7(a))

[144]. The polymer on the s-SWCNTs surface could be entirely removed with this approach. However, the polymer selectivity was not perfect and the semiconductor purity of s-SWCNTs was just 99.7%, making it unsuitable for high semiconductor purity s-SWCNTs. In 2017, Yu et al. took advantage of differences in solubility between PCz and s-SWCNTs in tetrahydrofuran (THF) (shown in Fig. 7(b)) [120]. s-SWCNTs purified by PCz were filtered and washed with THF multiple times. The ultraviolet-visible-near infrared ray (UV-vis-NIR) and Raman spectra demonstrate that most PCz were removed and the p-type transistors exhibit a 20-folds reduction in contact resistance. This solvent cleaning method could effectively remove the polymer on the surface of the s-SWCNTs unless it is wrapped on s-SWCNTs. The next challenge needs to be addressed is the removal of the wrapped polymer on s-SWCNTs. Another type method is the removal polymer from the prepared s-SWCNTs film on the substrate. In 2016, Brady et al. used rinsed and annealed method to remove PFO-BPy in s-SWCNTs film [145]. Vacuum annealing effectively decomposes and removes the side chains of conjugated polymer chains. However, it was difficult to remove the aromatic backbone of the conjugated polymer by the annealing method. Furthermore, the annealing process may damage the s-SWCNTs and introduce more defects, which acted as recombination centers to quench the photogenerated exciton reducing the photoelectric efficiency of the detector. In 2019, Ma et al. took a milder approach using the yttrium oxide coating-and-decoating (Y OCD) technique to remove polymers from the s-SWCNTs film [146]. In combination with the photolithographic process, the method could only treat the electrode contact area of the detector. No additional defects were introduced to the detector channel, and the photocurrent of the cleaned BFBD detector was increased by 17%. However, Y OCD cannot remove the polymers wrapped on the s-SWCNTs surface. In 2021, Yao et al. used a rapid annealing and cooling method (shown in Fig. 7(c)) which could thoroughly remove the wrapped polymers from the surfaces of s-SWCNTs, effectively reducing the contact resistance between the s-SWCNTs and metal electrodes [147]. Raman spectra showed no significant change in the G/D ratio of SWCNTs after rapid annealing, indicating that this method did not introduce additional defects to

the s-SWCNTs. The open-state current of the p-type transistor has increased by 6 times. This method needs to be further examined on optoelectronic devices. Although many works have been carried out in polymer removal, it is hard to draw a conclusion that s-SWCNTs film is polymer free. This is because that methods to characterize polymer removal of s-SWCNTs film are also a challenging topic.

5.2 Aligned s-SWCNTs arrays

Aligned s-SWCNTs arrays are ideal materials for preparing high-performance electronic and optoelectronic devices, which have received much attention in the last decade. Aligned s-SWCNTs arrays have been successfully prepared by CVD [148–150], floating-evaporation self-assembly [145], Langmuir-Schaefer [151], vacuum filtration [54], and dimension-limited self-alignment (DLSA) [111]. The DLSA method has been used to obtain s-SWCNTs film arrays with high orientation (orientation angle $< 8^\circ$), controlled density, and semiconductor purity $> 99.9999\%$ on 4-inch silicon wafers. The aligned s-SWCNT transistors exhibit better performance than the same technology nodes of silicon based transistors. Applying s-SWCNTs film arrays in detectors can avoid the negative effect of inter-tube junctions on the devices. The D^* and response speed of the detectors are expected to be further improved. The s-SWCNTs film arrays need to meet the following requirements to construct a high performance photodetector. (1) s-SWCNTs arrays need high density and certain thickness to ensure the light absorption of the detector. (2) The wrapped polymer of s-SWCNTs arrays needs to be removed to realize ohmic contact for both electrons and holes. s-SWCNTs arrays can maximize the characteristics of s-SWCNTs with high mobility and high carrier saturation rate, which is suitable for the application requirements of high speed and high frequency devices. In addition, excitons transition selection rules make s-SWCNTs have a polarization response. Polarization detection can use the polarization information of light other than intensity and wavelength, which can enhance the difference between the detection target and background in imaging applications and help to improve the recognition ability and accuracy of the detection target. Some 2D materials have been

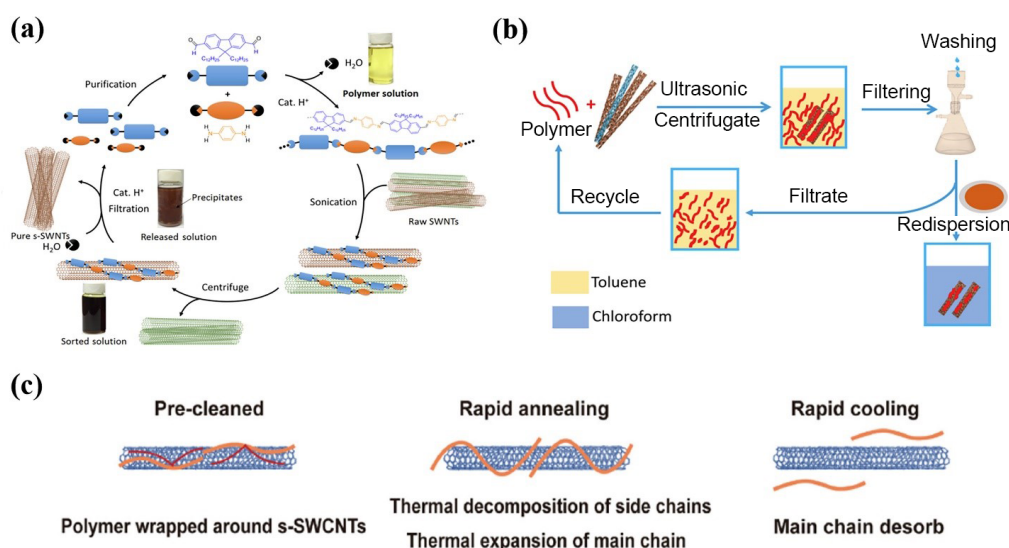


Figure 7 Removal of wrapped polymer on s-SWCNTs surface. (a) Mechanism of separation and purification and polymer removal. Reproduced with permission from Ref. [144], © American Chemical Society 2016. (b) Diagram of washing process to remove wrapped PCz. Reproduced with permission from Ref. [120], © American Chemical Society 2017. (c) Mechanism of rapid annealing to remove wrapped PCz. Reproduced with permission from Ref. [147], © Elsevier Ltd. 2021.

shown polarization response due to their exceptional lattice symmetry [152, 153]. However, these works mainly focus on the visible band, and the extinction ratio ($I_{\max}/I_{\min}$) cannot meet the actual application. Highly aligned s-SWCNTs arrays hold promise for preparing high extinction ratio SWIR detectors, which have potential applications in extreme weather detection, night vision, and camouflage/stealth.

5.3 Ideal s-SWCNTs film photodetector

Therefore, the ideal BFBD detector has the following requirements for s-SWCNTs film. First, the semiconductor purity of a uniform s-SWCNTs film needs to be greater than 99.9999%. As in a short channel detector, the presence of metallic SWCNTs will weaken built-in electric field and increase dark current. Second, the s-SWCNTs film has a high density or a certain thickness to ensure enough light absorption. In a tightly stacked s-SWCNTs film, the EQE of the detector is close to 34% when the thickness of s-SWCNTs film is greater than 7 nm [130]. Furthermore, s-SWCNTs must have a clear surface because the rapped polymers affect the contact quality between s-SWCNTs and electrodes. Finally, the s-SWCNTs network is replaced with well-aligned s-SWCNTs arrays. The disordered network s-SWCNTs has many inter-tube junctions causing large channel resistance of the detector, which increases the response time of the detector. Align s-SWCNTs film can effectively overcome this problem, making s-SWCNTs BFBD detectors suitable for high-speed and polarization detection. For the BFBD structure, the performance of the detector is dominated by the contact quality between the electrode and the s-SWCNTs. Currently, s-SWCNTs and electrodes are side contacts. Cao & Tang et al. demonstrated that some metals (such as Mo, Ni, and MoCo alloys) could form p-type end contacts by annealing or diffusion at high temperature [154–156]. The formation of end contacts effectively solves the problem of electrode size reduction and it may improve the performance of s-SWCNTs film BFBD photodetector with a certain thickness. However, there is only a solution for p-type end contact and no solution for n-type end contact because of n-type electrodes accessible oxidation property in high temperature process. The external environment of the s-SWCNTs, such as the substrate, also deserves to be considered. The commonly used substrates for BFBD devices are mainly silicon oxide and hafnium oxide. The substrate surface inevitably has some adsorbs, defect states, and surface undulations, which will quench the excitons and reduce the quantum efficiency of the detector [157]. Some 2D materials, such as hexagonal boron nitride (h-BN) with atomic level flatness and low defect states, are ideal substrate materials for optoelectronic detectors [158]. Therefore, it can be considered an ideal substrate for BFBD devices. For SWIR detection, an optimized s-SWCNTs film BFBD detector will further increase performance and show the benefits of optoelectronic integration, low cost, and easy process.

6 Monolithic three-dimensional (3D) optoelectronic integration

The integration of optoelectronic devices and silicon-based complementary metal-oxide-semiconductor (CMOS) chips is an important development direction for future information technology. As the limitation of silicon optical properties, silicon-based optoelectronic integrated systems require heterogeneous integration of other materials (like lithium niobate, III–V compounds, etc.) to achieve different functions [159, 160]. s-

SWCNT is inherently excellent electronic and optoelectronic material and can be used to prepare devices on any substrate. Therefore, there is more flexibility for s-SWCNT based 3D optoelectronic integration with a simpler process compared to traditional materials. There have been findings of advantages of s-SWCNTs suggesting that s-SWCNTs based integrated circuit may allow Moore's law to be extended in the future [161]. In 2015, Aly et al. demonstrated that, compared with traditional planar integration, the operation speed of a chip with 3D integration is increased by 23 times, the power consumption is reduced by 37 times, and the power density is comparable [162]. But the device's manufacturing temperature exceeds 1000 °C, which was the most significant barrier for traditional materials to realize 3D integration. Temperatures beyond 400 °C during the top system's fabrication would damage the underlying transistors and connection metals.

s-SWCNTs offer substantial benefits in 3D integration because of their naturally small size and low-temperature processing. The first s-SWCNTs 3D integrated system was reported by Shulaker et al. in 2017, based on the bottom-up construction of silicon logic circuits, s-SWCNTs logic circuits, resistive random-access memory (RRAM), and s-SWCNTs sensors below 200 °C processing temperature [163]. The 3D integrated system contains computational, sensing, and storage functions. Although further optimization was needed in terms of speed, power consumption, and system functionality, this work was pioneering in the field of s-SWCNT 3D integration.

For optoelectronic devices, s-SWCNTs have many intrinsic advantages in the 3D integration of optoelectronic devices. (1) The s-SWCNT is an ideal integration platform that can simultaneously build high-performance logic circuits and radio frequency (RF) circuits, LEDs, and photodetector. (2) The s-SWCNT is a direct bandgap semiconductor and the bandgap also can be adjusted with the nanotube diameter, which can cover the entire waveband of optical communication. (3) The low-temperature doping-free process can meet the requirement of the thermal budget window of 3D integration. (4) The s-SWCNT is a one-dimensional semiconducting material with no lattice mismatch with other substrates, and facilitates multilayer stacking for 3D integration. On the other hand, information can be collected, stored, and processed on the monolithic chip. The benefits of s-SWCNT in electronics and optoelectronics make it possible to construct optoelectronic integrated systems with the same 3D integration.

In recent years, some low-dimensional materials such as graphene [164], quantum dots [165], and 2D materials [166] have successfully achieved heterogeneous 3D integration with silicon materials, demonstrating the ability to collect and process information in a monolithic chip. In 2014, Kim et al. developed an s-SWCNTs film/silicon high performance heterojunction detector that operates in the visible wavelength range [167]. Under the illumination of an external light source, the use of various significant logic units such as a mixed optoelectronic AND gate and a 4-bit optoelectronic digital-to-analog gate was demonstrated.

In 2017, Liu et al. first reported electrically driven 3D optoelectronic integrated circuits (OEICs) [168]. An optical receiver consisting of a photodetector and a signal processing circuit was prepared on a high purity s-SWCNTs film. The detector could be used as a light-controlled gate to modulate the back-stage n-type FET. The optical receiver had a dynamic response range and a maximum response of 0.67 A/W at $V_{ds} = 3$ V. The optical receiver could operate as a stand-alone high-

performance subsystem or as part of the OEIC. Then, n-type FET and light emitters were prepared in (8, 3) & (8, 4) chiral s-SWCNTs, which could be used as a signal modulator to achieve three orders of magnitude modulation of the light intensity. Stacking the different functions of the optical receiver and emitter vertically not only increased the integration density of the chip but also achieved a multi-functional purpose in the limited chip area. As shown in Fig. 8(a), the entire device's active area only had a vertical thickness in the sub-30 nm, and the light emitted by the top layer of light-emitting devices could be received by the bottom layer of the detector. This 3D OEIC could be used as a data interaction system, where data stored in the top layer could be projected to the bottom layer through light emitters and receivers. The number of channels can be increased to improve the transmission rate further. The overall device response speed was in the order of kHz, mainly limited by the large devices resistance and parasitic capacitance.

Further optimizing the material and device structure is essential for building high performance, low power consumption, large scale, and high-speed multilayer stacked optoelectronic integrated circuits. Surface plasmonic polariton (SPP) bridges nanoelectronics and photonics because it can break the diffraction limit to achieve small optoelectronics devices. Slot antennas enable the coupling of far-field free-space light and unidirectional propagation of SPP by structural design. In 2017, Liu et al. constructed a 3D integration of passive slot antenna and active s-SWCNTs optoelectronics device to realize an electrically driven monolithic optoelectronic integrated circuit [169]. As shown in Fig. 8(b), the top layer is a passive device with two SPP gold bar waveguides. The bottom layer is an s-SWCNTs photodetector and an s-SWCNT LED with a subwavelength scale. Light emitted by s-SWCNT LED can propagate through the SPP waveguides, eventually absorbed by the s-SWCNT film photodetector on the other side to convert into current. All processes are CMOS-compatible low-temperature processes, demonstrating the potential application of electrically SPP integrated circuits for data transmission, repeaters, and modern computing systems.

In 2018, Liu et al. further investigated the 3D integration of slot

antenna SPP and s-SWCNTs film optoelectronics devices (shown in Fig. 8(c)) [170]. The near-field enhancement of the slot antenna can improve the photoresponse of the s-SWCNTs film photodetector. The slot antenna array could propagate SPP unidirectionally through the structural design with a coupling efficiency of 25.4% at 1200 nm. The experimental extinction ratio was 946, an order of magnitude larger than state-of-the-art unidirectional all-optical devices [171]. Further optimization of the s-SWCNTs film purity, especially the chiral s-SWCNTs film, and reduction of the propagation loss of the antenna will further improve the performance of the system.

Silicon-based passive optical devices are the most efficient and mature system to achieve on-chip transmission and control of photonic signals. High responsivity and speed can be obtained simultaneously by coupling detectors and waveguides. In 2020, Ma et al. combined passive devices that are commonly used in silicon-based photonics, such as gratings, waveguides, and multimode interference beam splitters, with s-SWCNTs active devices (shown in Fig. 8(d)) [142]. The s-SWCNTs film optoelectronic integrated system including optoelectronic conversion and logic processing functions is demonstrated by on-chip integration with s-SWCNTs film. s-SWCNTs based monolithic chip integrated systems demonstrate the potential of monolithic chip optical interconnects for modern computer and imaging systems.

For imaging applications, it is necessary to further improve the detector D^* and optimize the top detector pixel and bottom amplifier circuit architecture. For monolithic optical interconnection, optimizing the bandwidth and responsivity detector for modern communication applications is an urgent problem. The current limiting bandwidth of photodetector is due to the large series resistance and the capacitance of the device. The series resistance is mainly composed of channel and contact resistance. The channel resistance can be reduced by reducing the channel length and replacing the network s-SWCNTs with aligned s-SWCNTs. Reducing the contact resistance needs to remove the polymer rapped on the s-SWCNTs surface. For passive devices, it

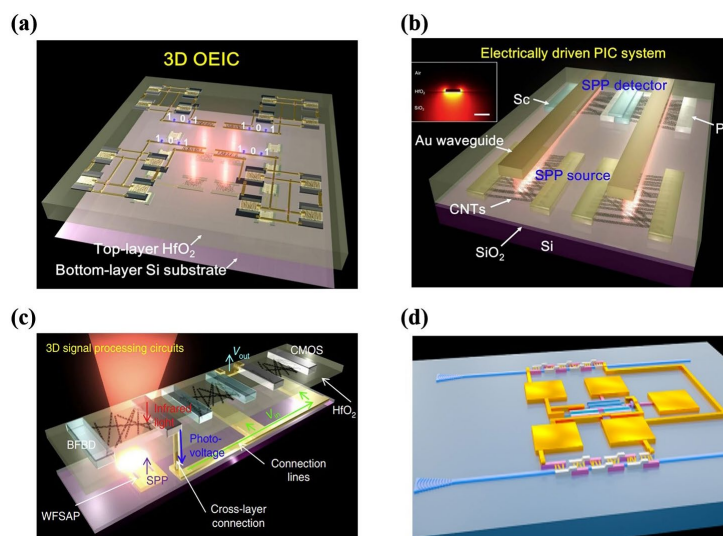


Figure 8 Monolithic 3D integrated demonstrations of s-SWCNTs film photodetector. (a) Electrically driven s-SWCNTs film based on the 3D optoelectronic integrated circuit. Reproduced with permission from Ref. [168], © Liu, Y. et al. 2017. (b) Electrically driven plasmonic interconnect circuit system based on s-SWCNTs film. Reproduced with permission from Ref. [169], © Liu, Y. et al. 2017. (c) Integration of the plasmonic-enhanced detector with s-SWCNTs film CMOS signal processing circuits. Reproduced with permission from Ref. [170], © Liu, Y. et al., under exclusive licence to Springer Nature Limited 2018. (d) Integration of waveguide s-SWCNTs film optoelectronic integrated system for wavelength division multiplexing system. Reproduced with permission from Ref. [142], © American Chemical Society 2020.

is necessary to reduce light loss through device structure design to ensure the performance of the system.

7 Conclusions and outlook

In this review, we summarize the development of high-purity s-SWCNTs film in recent years, focusing on the performances and characteristics of different structures of photovoltaic detectors based on high-purity s-SWCNTs film and the application of s-SWCNTs film in monolithic/3D integration. s-SWCNTs have great potential for the preparation of high performance SWIR detectors. But in terms of photodetector performance, there is still a gap between the current s-SWCNTs film photodetectors and traditional photodetectors. At room temperature, the D^* of conventional InGaAs (cutoff wavelength 1.7 μm) is greater than 10^{13} Jones, and extended InGaAs (cutoff wavelength 2.5 μm) is greater than 10^{10} Jones [13, 172]. In addition, due to the low-temperature processing and one-dimensional semiconductor structure characteristics, s-SWCNTs film also shows unique performance advantages in 3D/monolithic integration, monolithic optical interconnect, and modern communication and imaging systems applications. Large data centers for modern communications require high-speed, highly integrated, and low-cost optical interconnect systems to meet the demands of increasing data volumes. The reported 3-dB bandwidth of germanium photodiodes has exceeded 265 GHz at 1550 nm [173]. The intrinsic photocurrent response time of SWCNTs is in the order of picoseconds which has considerable potential in high-speed communication.

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Declaration of conflicting interests

The authors declare no conflicting interests regarding the content of this article.

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