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Overcoming the Bandwidth-Quantum Efficiency Trade-Off in Conventional Photodetectors

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<http://dx.doi.org/10.5772/intechopen.86506>

Abstract

Optical systems and microwave photonics applications rely heavily on high-performance photodetectors having a high bandwidth-efficiency product. The main types of photodetector structures include Schottky and PIN-photodiodes, heterojunction phototransistors, avalanche photodetectors, and metal-semiconductor-metal photodetectors. Vertically-illuminated photodetectors intrinsically present bandwidth-efficiency limitations, but these have been mitigated by new innovations over the years in quantum well photodetectors, edge-coupled photodetectors and resonant-cavity enhanced photodetectors for improved photophysical characteristics. Edge-coupled ultra-high-speed photodetectors have yielded high conversion efficiencies, and the active device structure of resonant-cavity-enhanced photodetectors allows wavelength selectivity and optical field enhancement due to resonance, enabling photodetectors to be made thinner and hence faster, while simultaneously increasing the quantum efficiency at the resonant wavelengths. Single-photon avalanche diodes have been developed, which combine an ultimate sensitivity with excellent timing accuracy. Further advances in addressing the bandwidth-quantum efficiency trade-off have incorporated photon-trapping nanostructures and plasmonic nanoparticles. Nanowire photodetectors have also demonstrated the highest photophysical performance to date.

Keywords: bandwidth-efficiency product, saturation current, quantum efficiency, photosensitivity, optical absorption, drift layers

1. Introduction

High-performance photodetectors (PDs) are key components in optical systems and microwave photonics applications. Examples include radio telescope arrays, optical fiber communication

systems and optically controlled phased array radar. Over the past several decades, the design principles of PDs and their technologies have become well developed, as various structures and fabrication/processing strategies have been established. Overall, the main types of PDs include *p-i-n* PDs, metal-semiconductor-metal (MSM) PDs, waveguide PDs (WGPDs) and traveling-wave PDs (TWPDs). These can be placed into three categories, according to the direction of optical propagation in the PDs, i.e., vertically-illuminated PDs (VPDs), edge-coupled PDs (EC-PDs) and resonant-cavity enhanced PDs (RCE-PDs). On the other hand, the lump and distributed PDs can be classified based on the component properties. The basic requirements for the PDs are high efficiency and high bandwidth, which are especially significant for systems operating at high data rates. In general, the quality of the different types of the high-speed PDs is characterized by the bandwidth-efficiency product. Another performance requirement of PDs is a high saturation current, especially for high power systems.

2. Vertically-illuminated photodetectors (VPDs)

The VPD comprises either the *p-i-n* or MSM structure. Upon optical illumination, electron-hole pairs generated in the device are separated by the electric fields within the *i*-region, thus contributing to a photocurrent through the processes of drift and diffusion. Simple-structured *p-i-n* PDs are the most common components in many optical systems. Yet, in order to improve on existing features of the conventional *p-i-n* PDs, different design variations, such as, those found in dual-depletion-region photodiodes (DDR PDs) [1, 2], uni-traveling-carrier photodiodes (UTC-PDs) [3–5] and avalanche photodiodes (APDs) [6–9], were extensively studied. Utilizing optical absorption layers combined with drift layers having wide bandgap, the DDR PDs typically have a larger bandwidth-efficiency product than that of conventional *p-i-n* PDs. In addition, the saturation current can be increased by optimizing the thicknesses of the absorption and drift layers [10]. To increase both bandwidth and saturation current, the UTC *p-i-n* structure is used, via leveraging the fast electrons during charge carrier transport. Thanks to the internal gain based on the avalanche multiplication effect, an enhanced sensitivity can be achieved by the APDs at the expense of higher operating voltages. MSM PDs based on the Schottky barrier [11–13] are another type of VPDs, which possess a smaller capacitance and lower dark current compared with that of the traditional design.

Due to broad and significant military and civilian applications, research on infrared detection and infrared photodetectors has intensified. In past decades, work on developing the operating temperature and spectral sensitivity capabilities of infrared photodetectors have become significant with the rapid development of photoelectric materials, for example, mercury cadmium telluride (HgCdTe) ternary alloys. Since the first synthesis of HgCdTe materials [14], HgCdTe infrared detectors with variable wavelength response have been manufactured by varying the alloy composition [15]. The amount of cadmium in the alloy can be selected in order to tune the bandgap which in turn determines the optical absorption of the material in the desired infrared range spanning the shortwave infrared to the very long wave infrared. As reported in [16, 17], HgCdTe infrared detectors with low frequency noise and high R_oA product in the long wavelength spectral region were demonstrated at liquid nitrogen

temperatures. As a result of large optical coefficients, more than 70% quantum efficiency has been achieved in HgCdTe infrared photodetectors [18].

Although HgCdTe is considered as an ideal material providing high degrees of freedom in infrared detector design, the difficulty in the fabrication and integration of such narrow bandgap materials (0–1.5 eV) is one practical limitation toward developing large-scale array applications [15]. Alternatively, photodetectors employing quantum wells in wide bandgap semiconductors (e.g., III-nitrides) were studied, such as, the so-called quantum well infrared photodetectors (QWIPs). Taking advantage of the artificial quantum well structure, the photocurrent is derived from optical absorption due to intersubband transitions involving many interacting and quantum-confined electrons. Based on previous theoretical and experimental investigations [19–22], Levine et al. [23] demonstrated the first QWIP, achieving a high peak responsivity at a wavelength of 10.8 μm. Thereafter, QWIPs were extensively explored [24–28] and related applications were developed [29–31].

However, *n*-type doped QWIP cannot utilize normal incidence illumination, and therefore optical coupling can be realized using gratings [32, 33], corrugated surfaces or 45° edge illumination [34, 35] to achieve promising results. Despite the relatively low quantum efficiency, the high uniformity and excellent reproducibility benefitting from mature growth and processing technologies represent main advantages of the QWIP over previous generation infrared detectors. It is the superior QWIP technology that makes large-scale focal plane arrays (FPA) possible. Examples include 1024 × 1024 pixel QWIP FPAs at mid-wavelength infrared and long-wavelength infrared [29], and 640 × 512 pixel four-band FPAs fabricated by monolithic stacking of different multi-quantum well structures [36, 37].

3. Edge-coupled photodetectors

Although various structures have been proposed and experimentally characterized, the bandwidth-efficiency product of conventional VPDs are limited due to the trade-off between quantum efficiency and bandwidth, which imposes a limit on the speed and sensitivity for photonic applications. For VPDs, increasing the thickness of the PD absorption layer offers the advantages of high quantum efficiency but suffers from a narrow bandwidth. Fortunately, the edge-coupled WGPD has been widely investigated as a promising approach to overcome the bandwidth-efficiency trade-off found in the VPD. The structure of the WGPD permits the bandwidth and efficiency to be specified almost independently because the quantum efficiency is determined by the waveguide length instead of the absorption layer thickness. However, the optical waveguide structure of the WGPD results in a low optical coupling efficiency [38], which is mainly caused by the mode mismatch between waveguide and optical fiber. In practice, efficient coupling is usually enhanced by a mode field converter [39]. Accordingly, depending on the structural configuration, WGPDs can be divided into mushroom-WGPDs and TWPDs.

As reported in [40], a bandwidth of 28 GHz and an efficiency of 25% have been achieved by the first ever high-speed edge-coupled WGPD. In 1991, WGPDs with double-core multimode

waveguide structures were proposed to address the coupling problem [41, 42]. The calculated coupling efficiency of the WGPD having such a structure can exceed 80% [43], which is regarded as a breakthrough in WGPDs for practical applications. By combining the structures of the waveguide and photodiode, the waveguide-fed photodiode (WG-fed-PD) is another design innovation to boost the coupling efficiency of the edge-coupled WGPD. Besides, the WG-fed-PD is ideal for implementation in optoelectronic integrated circuits. Previously, 70-GHz and 100-GHz photodetectors based on WG-fed-PD have been reported in [44, 45], respectively. Since WGPDs are categorically lumped devices, their bandwidths are limited by the RC time introduced by the parasitic capacitances and resistances. Kato et al proposed a new structure, which is the so-called the mushroom-WGPD having cladding layers that are wider than the core layer [46]. In such a structure, the capacitance as well as contact resistance can be reduced to obtain a larger bandwidth. In [47], a mushroom-WGPD with a bandwidth-efficiency product of 55 GHz was demonstrated. Furthermore, the distributed-element TWPD was proposed to overcome the RC bandwidth limitation of the WGPD. Although the structures of TWPD and WGPD are similar, the electrical properties of these two photodetectors are essentially different. Therefore, the TWPD bandwidth is mainly limited by the mismatch of the optical wave and microwave propagation velocities rather than the RC time delay.

As early as 1990, the design concept of the TWPD was reported by Taylor et al. [48], and a velocity-matched *p-i-n* TWPD [49] was proposed soon after. Since the first TWPD was experimentally demonstrated in 1994 [50], TWPDs with different configurations have been extensively studied [51, 54]. The photodiode element used in the TWPD can be a *p-i-n*, MSM diode [52] or avalanche diode. The TWPD structures are configured in various forms, in which the PD is based on the simultaneous operation of optical and electrical waveguides. Additionally, the photodiode elements can be distributed over the length of the waveguides. The so-called periodic TWPD or velocity-matched distributed photodetector (VMDP) is designed based on such a structure, where the optical waveguide is periodically loaded by discrete photodiodes [51, 53].

4. Resonant-cavity-enhanced photodetectors

As stated earlier, it is possible to mitigate the limited bandwidth-efficiency product in VPDs by means of increasing the length of the optical paths while retaining the thickness of the absorption layer. Thus, the resonant-cavity-enhanced photodetector (RCE-PD) was put forth as an alternative method to solve the trade-off conundrum between efficiency and bandwidth. Since the 1990s, a family of RCE-PDs was proposed, in which the photophysical performance was enhanced by placing the VPD within a Fabry-Perot resonator [55]. Since the photodiode elements incorporated inside the resonator are conventional VPDs, it should be noted that the electrical parameters of the RCE-PD, such as, the bandwidth, and dark and saturation currents, will not be enhanced. Based on microring resonators, Abaeiani et al. presented a new structure called the RCE-WGPD or microring PD (MRPD) [56], taking advantage of both the RCE-PDs and WGPDs. With such a structure, selective wavelength detection as well as a high efficiency-bandwidth product can be achieved. Without the mirrors used in traditional

RCE-PDs, the MRPDs are suitable for planar lightwave circuit integration. Various photo-sensitive devices based on MRPDs were reported in [57–59]. Moreover, the RCE-PDs based on grating were also presented in [60–62]. Due to the advantage of ultimate sensitivity combined with excellent timing accuracy, single-photon detectors, especially the single-photon avalanche diodes (SPADs), are important [63, 64]. As reported in [65, 66], the first RCE-SPAD was fabricated on a reflecting silicon-on-insulator (SOI) substrate.

5. Micro/nanostructured photodetectors

By adopting micro/nanostructures, photon-material interactions can be enhanced to address the trade-off between speed (bandwidth) and efficiency [67, 68]. The low-dimensional structures are able to control light for further interaction with the absorbing materials, excite the lateral propagation mode, and reduce surface reflection. Recently, silicon SPADs incorporating photon-trapping nanostructures were demonstrated [69]. Through diffraction of the vertically incident photons into the horizontal waveguide mode, the photons are trapped in the inverted pyramidal thin-film, and the absorption length is significantly increased to enhance the photon detection efficiency while retaining a low timing jitter. Similarly, a photon-trapping photodiode with micron- and nanoscale holes has demonstrated high-speed/high-efficiency performance [70], achieving an ultrafast impulse response of 30 ps FWHM (full-width at half-maximum), and a high efficiency of more than 50%. Another alternative technology being exploited to realize light-trapping in thin-film PDs is plasmonic nanostructures [71–74]. Unlike the photon-trapping mechanism enabled by micro/nanoholes, the metallic nanoparticles in plasmonic nanostructures act as sub-wavelength scattering centers, which allow coupling of the incident light into the semiconductor.

With the development of advanced nanofabrication technologies, photodetectors with integrated nanowires, i.e., nanowire PDs, have been realized and studied extensively [75–79]. In particular, several demonstrations of high-speed nanowire PDs were reported. In [80], a photoconductor with intersecting InP nanowires was demonstrated to obtain a pulse response of 14 ps FWHM at 780-nm wavelength irradiation. Compared with using bare core nanowires, higher response was achieved in MSM PDs using Schottky-contacted GaAs/AlGaAs core/shell nanowires [81]. In [82], nanopillar-based APDs have exhibited a 200-GHz gain bandwidth product at 1060-nm illumination.

6. Conclusion

This chapter introduces the main types of PD structures including the Schottky and PIN PDs, APDs, MSM PDs, and heterojunction phototransistors. Vertically-illuminated PDs have inherently low bandwidth-efficiency products but have been mitigated by new innovations in QWIP, edge-coupled, RCE and nanostructure, designs. Since the 1990s, RCE and WG PDs have been explored to address the bandwidth-quantum efficiency trade-off. RCE-SPADs have been recently developed for the ultimate in sensitivity while maintaining a low timing jitter.

CMOS- and lithography-compatible processes have been adopted in the design of SOI-based SPADs. Photons can be diffracted, guided and absorbed in different pixels, especially for tightly-patterned silicon photomultipliers. Nanostructured materials and nanoplasmonics have been exploited for enhanced photon trapping, coupling and absorption in MSM PDs and APDs, for the highest bandwidth-efficiency product.

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