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REVIEW ARTICLE

Single-photon avalanche diode detectors based on group IV materials

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Abstract

Today there are several types of photodetectors that can cope with the task of detecting a single photon, however, avalanche photodiodes are most widely used for applications in fiber-optic communication systems and quantum cryptography. In the past 5 years experimental fabrication of single-photon avalanche detectors within conventional complementary metal–oxide–semiconductor technology and by the method of molecular beam epitaxy have made possible many demonstrations of avalanche photodetectors with exceptional performance characteristics and opened wide perspectives for development of devices of new generation. In this work, we review state-of-the-art designs of single-photon avalanche photodiodes based on group IV materials, their operating characteristics, and achieved values of basic parameters, as well as the methods of their synthesis, and outline the perspectives of using such structures in emerging device applications.

Keywords Quantum information technology · Single-photon detector · Avalanche photodiode · Silicon photomultiplier · Two-dimensional material · Silicon · Germanium · Molecular beam epitaxy

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Background

Currently, the world is full of wires, radio waves, and optical fibers. Modern communication systems use them as channels for information exchange. But it often becomes necessary to transmit some very important, secret information. However, using ordinary communication channels, one cannot guarantee the secrecy of the transmitted data. Therefore, for the exchange of secret information, systems for transmitting information over a high-speed physical channels were created, the secrecy of which is ensured by the laws of quantum physics. Thus, the quantum cryptographic systems emerged. Quantum cryptography began to develop in 1984, although the coding principle on which the system is based was invented at the beginning of the last century [10]. And like any young science, quantum cryptography still contains many unresolved problems. One such problem is the data transfer rate in quantum cryptography systems. Many research groups engaged in the study of quantum cryptographic systems strive to create a system not only with maximum secrecy of information exchange but also with a high data transfer rate. However, with an increase in the data transfer rate in quantum cryptographic systems, problems arise, associated with the detection of single photons [14].

Today, there are several types of photodetectors that can cope with the task of detecting a single photon, however, the avalanche photodiodes (APD) are most widely used for applications in fiber-optic communication systems and quantum cryptography. Detectors based on avalanche photodiodes are relatively inexpensive and compact for quantum cryptography systems [43, 46]. Recent integration of avalanche photodiodes fabrication into standard complementary metal–oxide–semiconductor (CMOS) technology allowed researchers to create optoelectronic circuits on the same silicon chip, enabling their cheap and massive fabrication [23]. Therefore, at present, the main solution for the practical detection of single photons is the use of single-photon avalanche diodes [56].

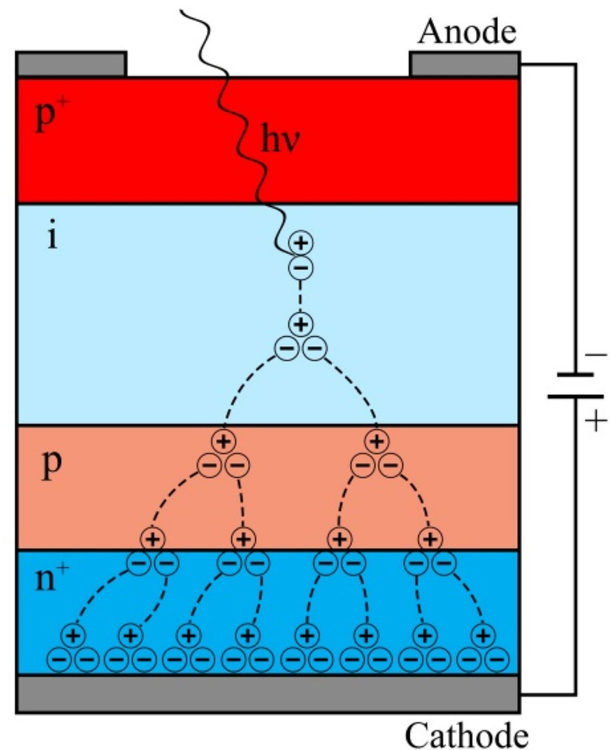

Fig. 1 Cross-section of avalanche photodiode and its operating principle

Avalanche photodiodes are highly sensitive semiconductor devices that convert light into an electrical signal due to the photoelectric effect. They can be considered as photodetectors providing internal amplification through the avalanche multiplication effect. From a functional point of view, they are solid-state analogs of photomultipliers. Avalanche photodiodes are more sensitive than other semiconductor

photodetectors, which makes it possible to use them for registration of extremely low light powers. The main difference between an avalanche photodiode and a conventional photodiode is the internal signal amplification based on avalanche electron multiplication of the signal. If the layer structure of a conventional photodiode has the p+–i–n+form, then a p-layer (p+–i–p–n+) is added to APD (Fig. 1). Moreover, the profile of the distribution of dopants is chosen so that the p-layer has the biggest resistance and, consequently, the largest electric field value. When the i-layer is exposed to light, electron–hole pairs are formed. Due to the small field, the carriers move towards the corresponding poles (anode or cathode). When free electrons from the i-layer enter the p-layer, their acceleration becomes more noticeable due to the high electric field in the p-layer. Accelerating in the conduction band of the p-layer, such electrons accumulate energy sufficient to excite other electrons from the valence band into the conduction band. This process is called avalanche amplification or multiplication of the primary photocurrent.

In avalanche diodes, as well as in their non-avalanche counterparts, it is necessary to achieve maximum quantum efficiency. In addition, it is important that the multiplication of carriers in the cross section of the area illuminated by the detected radiation remains uniform. High quality materials with practically no defects and dislocations must be used, otherwise the resulting local increases in the electric field will lead to the formation of a premature avalanche or microplasma.

To create detectors of single photons, APDs can be made on the basis of silicon (Si), germanium (Ge), gallium nitride (GaN), HgCdTe, or III–V heterostructures, such as InGaAs/InP and InGaAs/InAlAs, depending on the desired operating wavelength [3].

For optical communication systems and quantum communication applications, the ability to operate at the low-loss wavelengths of 1310 nm and 1550 nm is crucial. Free space and LIDAR applications also demands operation in this spectral range [45, 50]. All these require development of fast-speed and high-sensitive single-photon avalanche diode detectors of short-wave infrared range (SWIR), based primarily on group IV materials, such as silicon and germanium.

The aim of this review is to create a comprehensive picture of the state-of-the-art designs of single-photon avalanche photodiodes based on group IV materials, their operating characteristics, and achieved values of basic parameters, as well as the methods of their synthesis, and outline the perspectives of using such structures in emerging device applications.

Modes of avalanche photodetectors operation

There are two modes of operation of avalanche photodetectors: linear mode and Geiger mode. In the linear mode the average number of signal photoelectrons n_s remains proportional to the number of exciting photons n_p so that $n_s \sim \eta \cdot M \cdot n_p$, where η and M are the quantum efficiency and the avalanche multiplication factor of APD, correspondingly.

Avalanche photodiodes of a special design, capable of operating not only in a linear mode but also in a highly nonlinear key mode, which is referred to in the literature as the Geiger mode [6], open new possibilities for achieving the limiting sensitivity of photodetectors. As a rule, the term APD is applied to a device if it operates below the breakdown voltage in a linear mode, when the output photocurrent is directly proportional to the input optical power. On the contrary, for devices operating in Geiger mode, the term single-photon avalanche detector (SPAD) is commonly used.

In the Geiger mode, the bias voltage of the diode exceeds the threshold voltage of the avalanche breakdown. Therefore, the internal electric field becomes so strong that a high photocurrent gain can be obtained. Under these conditions, excitation of SPAD by a single photoelectron leads to the formation of a self-sustaining avalanche process in the p–n junction of the diode, which leads to the formation of a macroscopic signal response in SPAD load, while the internal noise turns out to be vanishingly low [20].

Operation at such a high gain in Geiger mode inevitably leads to a very high current flowing in the SPAD diode. It must be constantly monitored to have time to prevent damage to the photodetector using an appropriate quenching circuit. In its simplest form, the quenching circuit can be implemented with a current-limiting resistor in series with an avalanche photodiode, which will quench the avalanche if the resistor is large enough. However, such schemes usually have a long recovery time, which limits the maximum count rate. For this reason, most of the commercially available SPAD photon counting modules have an active quenching circuit. It detects the occurrence of an avalanche and then decreases the bias voltage at the avalanche photodiode below the breakdown voltage for several nanoseconds.

So, the systems based on SPADs usually consist of two main parts: the SPAD itself, and the electrical avalanche quenching scheme. Thus, the performance of such devices depends not only on the SPAD characteristics, but equally on the properties of quenching circuit.

In this review, we will consider avalanche photodiodes operating mainly in the Geiger mode, as well as their basic constructions and operating characteristics.

Fundamental characteristics of single-photon avalanche detectors

Like any other device, a single photon detector has a set of parameters that characterize the efficiency of detection of light quanta.

Photon detection efficiency (PDE) is the probability of registering a single photon, in other words, the ratio of the number of registered photons to the total number of incoming photons. Achieving the maximum value of this parameter is especially desirable for photons of three wavelengths: 810 nm, 1310 nm, and 1550 nm, for which the losses in the optical fiber reach its minimum values. For the purposes of quantum technologies, the value of this parameter should be ideally close to unity [16].

Dark count rate (DCR) is the number of false pulses in the detector per unit time in the absence of a photon. This value is a characteristic of the intrinsic noise of the detector [12]. DCR is defined as a normalized numerical value for the performance in the absence of radiation. DCR is dependent on temperature conditions and bias value. Dark counts may originate from thermal or tunnel excitation mechanisms. At sufficiently high temperatures, thermal excitation will make the main contribution to the DCR, while at low temperatures, but in a strong electric field, the main contribution to the DCR will be made by tunneling excitation caused by excess bias [7].

Dead time is the time after the registered pulse, during which it is impossible to register the next photon. For example, by sending individual laser pulses with a low frequency (~kHz) to the SPAD, one can skip such a phenomenon as the removal of the detector from the operating point mode due to blinding, which occurs at a pulse repetition rate higher than a certain value of order of MHz. Blinding is associated with the dynamics of the processes responsible for the restoration of the electric potential on the diode.

Timing jitter (time resolution) is usually defined as the total time uncertainty between the incidence of photons and the corresponding output electrical signal, which includes the contribution of the SPAD itself and the avalanche quenching system [12].

During avalanche formation, some carriers are captured by defects and unnecessary impurities in the multiplication layer. Subsequently, these carriers may be released and can cause unwilled avalanche processes called residual pulses. Therefore, an important SPAD parameter is the afterpulsing probability, or probability of occurrence of residual pulses, which is calculated as the number of residual pulses arising in relation to the previously detected photons over a certain time interval.

Recently, extended and high-speed quantum key distribution (QKD) systems have stimulated the development of high-speed single-photon detectors [16]. Since transmission secrecy requires the presence of no more than one photon in each laser pulse, an extremely high requirements are imposed on photodetectors. They must have high quantum detection efficiency, low noise, small dead time, low jitter, and a sufficiently low dark count rate [7].

Single-photon avalanche photodiodes based on group IV materials

Single-photon avalanche diode detectors based on silicon

Single-photon avalanche diodes based on group IV materials (including silicon and germanium) and fabricated with standard CMOS technology can be very promising candidates for use in the area of single-photon detection. In comparison with III-V devices, silicon/germanium SPADs traditionally exhibit considerably reduced afterpulsing effects combined with being the inexpensive device platform. Nowadays, the efforts of researchers are aimed on the improvement of such devices in terms of low noise, low cost, and compatibility with traditional circuits to make use of all the advantages of the silicon-based system [38].

One of the key components of modern SPADs is so called guard ring, which prevents premature edge breakdown and improves the electric field distribution to the intended multiplication region [9, 24, 36]. The choice of proper physical dimensions, especially the active radius and the size of the

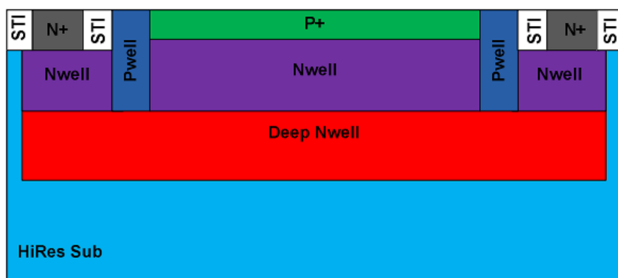

Fig. 2 Cross-section of the SPAD with guard ring [32]

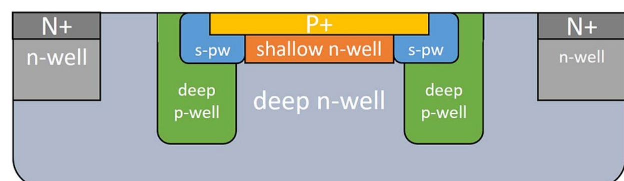

Fig. 3 Cross-section of the SPAD with shallow p-wells (s-pw) guard ring [1]

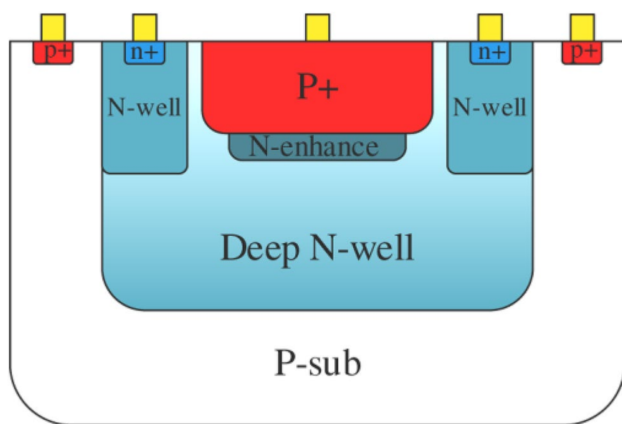

Fig. 4 Cross-section of the SPAD with virtual guard ring [51]

guard ring, is important for the better performance of silicon SPADs [38].

In 2015 Malass et al. [32] presented the performance characteristics of SPAD fabricated in standard 180 nm CMOS process. The active area was p + /n-well junction in deep n-well on p-substrate with high resistivity (HiRes Sub) (Fig. 2). To avoid premature breakdown, double p-well/STI (shallow trench isolation) guard ring was implemented. The low doped p-well guard ring was added to separate the multiplication region from the STI implant to reduce high dark noise due to faulty detections triggered by carrier injections from the STI interface into the multiplication area.

The implemented SPADs have shown DCR below 10 kHz at 15 °C with low afterpulsing probability (0.2% at 300 mV), rather good photodetection efficiency (20%) and very good time resolution of 80 ps at the wavelength of 450 nm [32].

In 2018 Accarino et al. [1] reported a square-shaped photo-carrier diffusion SPAD designed with narrow depletion region and wide photo collection region (Fig. 3). The SPAD was manufactured in standard 180 nm CMOS technology. The p + region was aimed to shallow n-well junction. The shallow n-well layer enhanced the electric field beneath the p + active area while the guard ring, implemented by shallow p-wells (s-pw) into a deep p-well, effectively reduced the electric field to prevent the active junction from premature breakdown. The width of the guard ring and its distance from the n-well were designed to achieve the lowest possible electric field value at the p-n interface. The deep n-well acted as a photocollecting region, allowing collected photons to diffuse into the avalanche region. These authors achieved extremely low DCR (less than 1 kHz) with a photodetection efficiency greater than 50% at the bias of 4 V. The timing jitter performance was also rather high.

The next paper by Wang et al. [51] have discussed a SPAD designed with standard 180 mm CMOS process with p + /n-well junction structure and multiplication region surrounded by a virtual guard ring (Fig. 4).

The multiplication region with high electric field was implemented in the junction between the p + and n-well layers. The central n-well implantation area had a retrograde doping profile (doping concentration increased from a low level at the surface to a high level, deeper into the wafer). This layer enhanced the electric field in the central anode active region and served as a virtual guard ring. The authors achieved photodetection efficiency of larger than 43% in the spectral range from 650 to 950 nm at 5 V of excess bias and DCR lower than 1.5 kHz at room temperature [51].

Finally, in one of the most recent works Shin et al. [38] proposed Si SPAD with a deep p-substrate virtual guard ring fabricated through deep well diffusion via 110 nm CMOS technology process. As a deeper multiplication region requires a deeper guard ring depth, the deep n-well (DNW) layers were doped separately and the separate DNWs were connected through a diffusion process to obtain the deep p-substrate virtual guard ring (Fig. 5). STI layers were added between n + source and drain (NSD) and p + source and

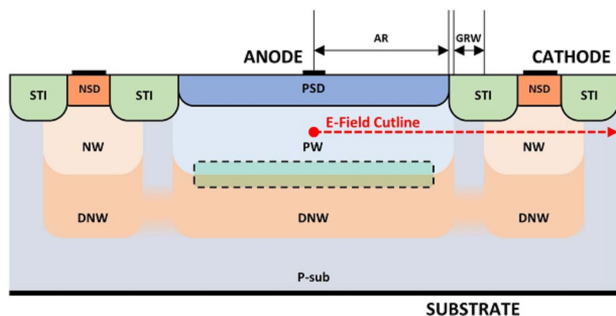

Fig. 5 Cross-section of the SPAD with deep virtual guard ring [38]

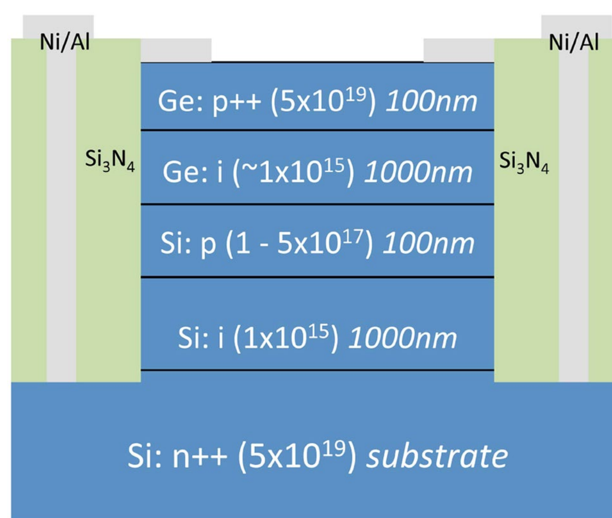

Fig. 6 Cross-section of the multilayer germanium-on-silicon SPAD [52]

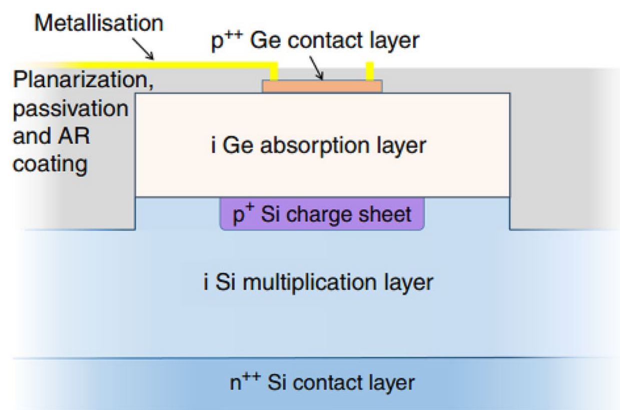

Fig. 7 Cross-section of the planar germanium-on-silicon SPAD [47]

drain (PSD) layers to exclude the formation of high electric field between anode and cathode. The deep virtual guard ring surrounded the multiplication area (PW/DNW interface in the center) that prevented the leakage of the electric field at the edge of multiplication region while maintaining low doping concentration of p-substrate compared to the conventional guard ring generated by doping. The authors have also investigated the effect of the physical variation of the active radius and width of the guard ring on the device characteristics.

All the presented silicon SPADs designed in a standard CMOS technology allow researchers simple integration with the highly developed conventional technology, while showing excellent operating characteristics and cost effectiveness.

Germanium-on-silicon avalanche photodetectors

Effective and reliable fabrication of SPADs by the method of molecular beam epitaxy has made possible many demonstrations of germanium-on-silicon avalanche photodetectors with impressive performance characteristics [15, 18, 27, 34, 39, 45, 48]. In germanium-on-silicon detectors light absorption occurs in germanium layer while the multiplication takes place in silicon. The most perspective method of fabrication of these structures is molecular beam epitaxy of germanium on silicon substrate. This technology made it possible to achieve in germanium/silicon detectors operating characteristics comparable with those in InGaAs/InP competitors [13].

The first single-photon detector using a germanium absorber coupled with silicon multiplication region was demonstrated in 2002 by Loudon et al. [26]. An improvement in detection efficiency at the wavelength of 1210 nm compared with that of pure silicon structure has been shown in SiGe/Si multiple quantum wells structures proposed by this authors.

In 2011 Lu et al. [30] reported germanium-on-silicon SPAD with single-photon detection efficiency of 14%, DCR of 10^8 s^{-1} and timing resolution of 117 ps at the temperature of 200 K for the wavelength of 1310 nm.

In 2013 Warburton et al. [52] proposed multilayer germanium-on-silicon structures depicted in Fig. 6. They have shown single-photon detection efficiency of 4% at 1310 nm wavelength and temperature $T = 100$ K with a dark count rate of $6 \cdot 10^6$ s^{-1}, resulting in the low noise equivalent power (NEP) of $1 \cdot 10^{-14}$ $W \cdot Hz^{-1/2}$. They have also first reported about 1550 nm wavelength detection efficiency measurements with germanium-on-silicon single-photon avalanche diode detector.

Vines et al. [47] have recently introduced new generation of group IV devices for single-photon detection in near infrared (NIR) and short-wave infrared (SWIR) regions. They report on the first normal-incidence, planar germanium-on-silicon SPAD with high-performance single-photon operation, illustrating high-efficiency detection and low afterpulsing effects. The devices described in the paper used the separate absorption, charge and multiplication (SACM) structure with antireflection (AR) coating (Fig. 7). The incident SWIR radiation was absorbed in the Ge absorption region and the signal amplification took place in the Si multiplication region. In between these regions, a selectively implanted charge sheet was used to control the electric field so that the field was high enough in the multiplication region to ensure that avalanche breakdown was reached and low enough in the absorption region to prevent band-to-band and trap-assisted tunneling. A modest electric field was maintained in the Ge layer to allow efficient drift of photogenerated electrons into the multiplication region [47].

These planar SPADs had a sharp breakdown indicating a low multiplied dark current, previously found to be a strong indicator of the desired low DCR performance.

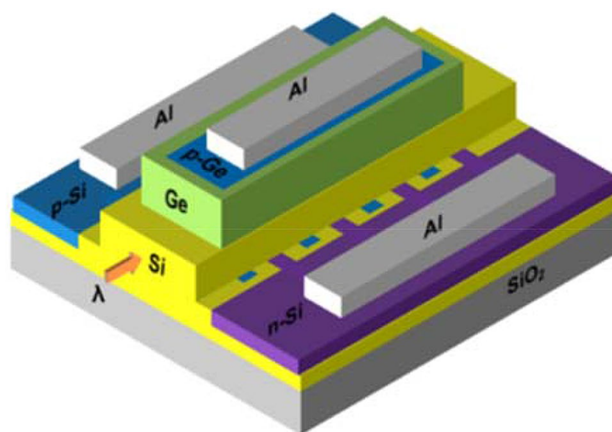

Fig. 8 Structural diagram of a three-terminal silicon/germanium waveguide avalanche photodiode [55]

The single-photon detection efficiency at 1310 nm reached 38% at $T = 100$ K and the noise equivalent power of $1.9 \cdot 10^{-16}$ W·Hz$^{-1/2}$ at $T = 78$ K was achieved. At this early stage of development, these are very encouraging values for the future realization of germanium-on-silicon SPAD focal plane arrays [47].

The same authors have achieved high single photon detection efficiency of 38% at 1310 nm with an operating temperature 125 K using planar geometry germanium-on-silicon SPAD [21]. They have also reached noise equivalent power value of.

$3 \cdot 10^{-16}$ W·Hz$^{-1/2}$ while having reduced afterpulsing compared to InGaAs/InP based SPADs for the same operating conditions.

Thorburn et al. [45] have recently used the same geometry as Vines et al. [47] to produce highly efficient planar geometry germanium-on-silicon SPAD with the spectral range extended into SWIR region. Low dark count rates below 100 kHz at the temperature of 125 K were achieved in these devices. Single-photon detection efficiencies of up to 29% were measured at the wavelength of 1310 nm at 125 K. Noise equivalent power of $9.8 \cdot 10^{-17}$ W·Hz$^{-1/2}$ and jitters less than 160 ps were obtained, demonstrating the potential of these devices for highly sensitive and fast speed operation in the SWIR region [45].

The results obtained by Vines, Thorburn and others show the perspectives of germanium-on-silicon SPADs operating at near-room temperature, with low DCR, low afterpulsing and high count rate for the wavelengths of 1310 and 1550 nm.

Another construction of germanium-on-silicon avalanche detectors incorporates a waveguide structure [4, 33, 40]. For example, in 2017 Martinez et al. reported on single photon detection efficiency of 5.27% at 1310 nm and dark count rate of 534 kHz at 80 K for such type of devices [33].

A novel waveguide-coupled germanium-on-silicon avalanche photodiode detector have been recently implemented by Zeng et al. [55]. Light is coupled from an optical fiber via a grating coupler to a silicon waveguide and is then coupled to germanium block above silicon for absorption (Fig. 8). Such CMOS-compatible avalanche photodiode with three electric terminals was demonstrated to have breakdown

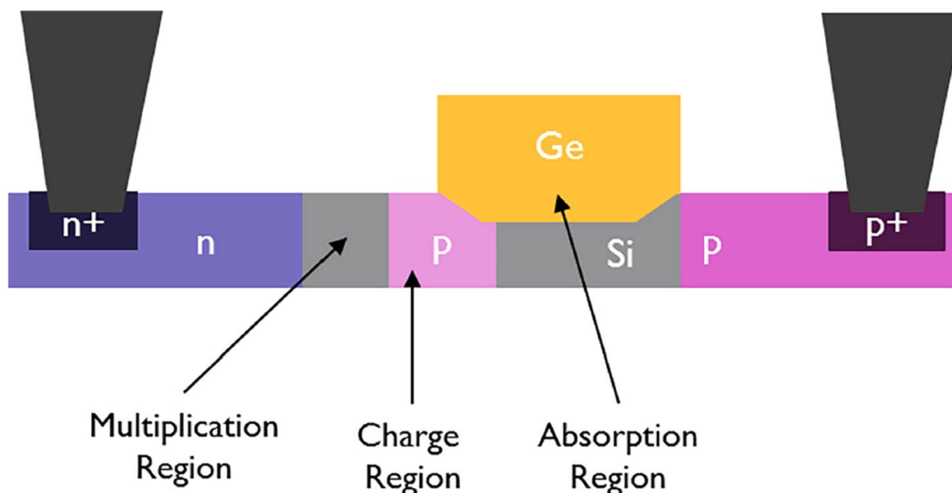

Fig. 9 Schematic diagram of Si-contacted waveguide integrated Ge/Si based lateral separate absorption charge multiplication avalanche diode [41]

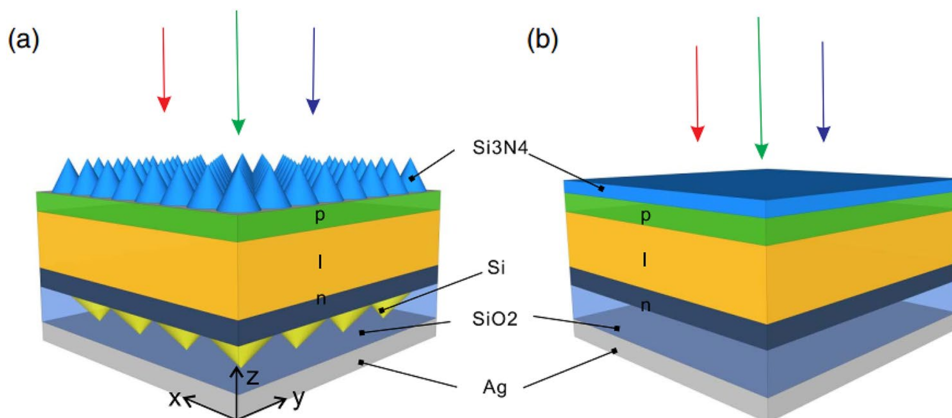

Fig. 10 Cross-sections of **a** nanostructured and **b** flat-film SPADs [31]

voltage of – 6 V, bandwidth of 18.9 GHz, DC (direct current) photocurrent gain of 15, open-eye diagram at a data rate of 35 Gb/s, and sensitivity of – 11.4 dBm at the data rate of 25 Gb/s. This three-terminal avalanche photodetector allows high-yield fabrication in the standard CMOS process and provides robust high-sensitivity operation under small voltage supply [55].

One other geometry of the device structure for germanium-on-silicon avalanche detectors was designed by Srinivasan et al. [41]. Separate absorption charge multiplication (SACM) avalanche photodiode was designed such that germanium formed the waveguide in the absorption region. The multiplication region was in silicon layer and it was separated from germanium area using the charge region (Fig. 9). The device was fabricated using an established silicon photonics technology without additional process complexity and contacts only on silicon. The doping profile for the charge region was chosen to have high electric field in the multiplication region, while maintaining enough electric field in germanium to extract the photogenerated carriers. The charge region protected germanium from high electric fields associated with high reverse bias. The device had the responsivity of 25 A/W and 29 A/W at 1310 nm and 1550 nm respectively, RF (radio frequency) gain of 11, and the bandwidth of 27 GHz. Wide open eye diagrams were demonstrated for up to 50 Gb/s data rates. These results show great potential of such avalanche photodiodes for optical transceivers operating at 400 Gb/s and beyond [41].

Certain efforts are aimed on the development and creation of SPADs with silicon/germanium nanostructures. The results of these works show that in future nanostructured SPADs may overcome traditional ones in terms of efficiency and frequency parameters [2, 31, 42, 53, 54].

For example, in 2014 Stepina et al. [42] have shown the possibility of using germanium quantum dots on silicon and silicon-on-insulator substrates for single-photon detection. At the same time Ali and Richardson [2] have fabricated p-i-n photodetectors with silicon–germanium superlattices exhibiting absorption up to 1770 nm which can be used as absorption regions for silicon-based avalanche photodiodes.

Then, Ma et al. [31] proposed nanostructured silicon SPAD based on a thin film SPAD with nanocone gratings coated on both sides (Fig. 10). The top silicon nitride nanocone grating serves as broadband antireflection coating. On the other hand, the bottom silicon nanocone grating aims to scatter the light strongly toward the lateral direction and its parameters are adjusted to ensure the maximum absorption. The optical and electrical simulations have shown significant performance enhancement compared to conventional silicon SPAD devices. The presented nanostructured SPAD combines high detection efficiency over a broad spectral range and low timing jitter, solving the problem of coexistence of these two parameters in silicon SPADs [31].

Another method of creation of nanostructured SPAD may be lithography with subsequent etching as it proposed by Zang et al. [54]. They demonstrated light-trapping, thin-junction silicon single-photon avalanche diode, diffracting the incident photons into the horizontal waveguide mode, thus significantly increasing the absorption length (Fig. 11). This nanostructured SPAD again had improved near infrared detection efficiency while keeping the timing jitter at the low value of 25 ps.

Use of other group IV materials besides silicon and germanium (primarily, tin) for creation of SPADs is also considered by researchers [40, 57]. For example, Zhang et al. [57] showed mesa-type normal incidence SACM GeSn/Si APD with rather high responsivity and low dark current at the wavelengths of 1310 and 1550 nm. Then, Soref et al. [40] reported on design and simulation of waveguide-based GeSn/Si SPADs for 1550 nm wavelength. They have shown that GeSn/Si system can be a good candidate to realize SPADs operating at room temperature for integrated quantum photonics. However, these investigations are still at the very initial stages.

The reviewed results illustrate clear potential for integration of group IV materials SPADs with silicon CMOS technology for low-cost, high data rate SPAD array imaging in the NIR and SWIR bands, which are critical for emerging

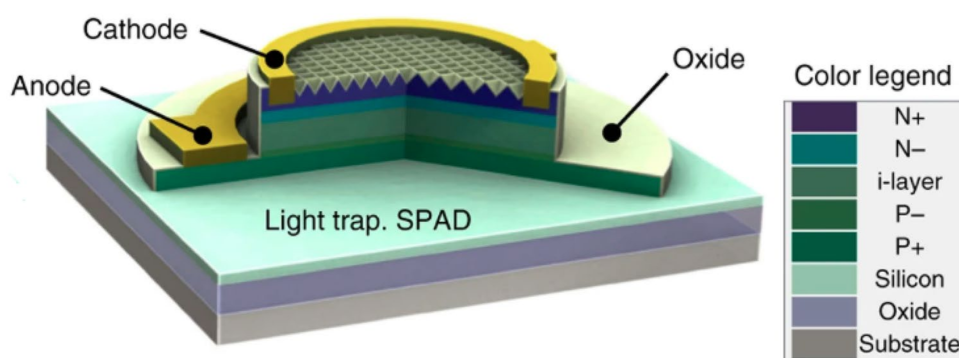

Fig. 11 Cross-section of light-trapping SPAD [54]

LIDAR applications (for example, in autonomous cars) and optical communication systems, including quantum information technology.

Perspectives

Single photon detectors are one of the most important elements of any communication system based on the principles of quantum cryptography. They must have high quantum detection efficiency, low noise, and a sufficiently high count rate. Avalanche photodiodes based on group IV elements are good and practical single-photon detectors in this area.

Single-photon avalanche photodiodes operating in Geiger mode are the most practical devices for detecting ultra-low intensity light in the near-infrared range with very high timing resolution (of order of a few tens of picoseconds) due to the impact ionization mechanism. Over the past decade, the academic and industrial communities have made tremendous efforts to improve the performance of SPADs. In addition, new devices like negative feedback avalanche diodes (NFAD) and SPADs with self-quenching mechanisms appear which can improve SPAD performance and remove the limitations of quenching electronics. In turn, various technologies have been discovered in the field of quenching electronics.

The characteristics of modern photodiodes make it possible to provide a single photon counting mode. Therefore, single-photon detectors are increasingly used in such areas as fiber-optic communication systems, quantum cryptography, quantum key distribution, positron emission tomography, optical reflectometry, super-resolution microscopy, time-resolved Raman spectroscopy, near infrared imaging, all kinds of LIDAR technologies for open-space and free-space communications. They can be also utilized in rather more emerging or future applications where single-photon sensitivity and high precision time-of-arrival detection are critical.

In the future, the development and evolution of SPADs for NIR and SWIR ranges will continue to move science in this direction, as SPADs themselves are need to be improved. This requires further research and additional efforts aimed on the improvement of the performance characteristics and overall optimization of SPADs, as well as on creation of high-quality materials and discovery of new ones. Key parameters to consider in device design are single-photon detection efficiency, dark count rate and afterpulsing probability. Therefore, high PDE and low DCR are two of the most important design goals for future devices. Reducing the size of the SPAD can effectively reduce DCR and afterpulsing probability, and corresponding research is already conducted. However, coupling with optical fiber can be a significant challenge when making small SPADs.

Recent advances in fabrication of avalanche photodetectors in CMOS technology and by the method of molecular beam epitaxy paved the way for high-performance germanium-on-silicon SPADs. While InGaAs/InP photodiodes are still the best choice for creation of infrared photodiodes, silicon/germanium devices have already proved to be competitive in terms of performance characteristics with their III-V analogs. Main advantages of group IV devices are direct compatibility with existing high-quality silicon technology and relative cheapness. However, the DCR value of germanium-on-silicon SPADs should be improved to achieve the level of their III-V and II-VI counterparts [17, 25, 37, 44, 49].

Operating parameters of SPADs based on group IV materials may be improved by refinement of their synthesis technologies in the method of molecular beam epitaxy as well as by the use of strained silicon/germanium heterostructures [8, 28, 58]. Another way to improve the characteristics may be the search for completely new device configurations (for example silicon photomultipliers) [11, 22, 35], active involvement of nanostructures technology [5], as well as the use of brand new materials within the same group IV elements (for example, 2D materials such as silicene, germanene, and stanene) [19, 29].

Thus, at the moment, targeted joint efforts of theorists and experimenters, search for novel device structures, computer simulation and analysis of obtained results are crucial to improve the performance characteristics of single-photon avalanche detectors.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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