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Modeling the characteristics of avalanche photodiodes based on Ge/Si

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Abstract. In this article, the planar structure of an avalanche photodiode based on Ge/Si is designed. The dependences of the gain and bandwidth on the bias voltage for different thicknesses of the absorption and multiplication layers of an avalanche photodiode based on Ge/Si are presented.

Keywords: optoelectronics, avalanche photodiode, impact ionization, planar structure, gain-bandwidth product

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Моделирование характеристик лавинных фотодиодов на основе Ge/Si

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Аннотация. В данной статье выполнено проектирование планарной структуры лавинного фотодиода на основе Ge/Si. Представлены зависимости коэффициента усиления и полосы пропускания от напряжения смещения для разных толщин слоев поглощения и умножения лавинного фотодиода на основе Ge/Si.

Ключевые слова: оптоэлектроника, лавинный фотодиод, ударная ионизация, планарная структура, произведение, коэффициент усиления на полосу пропускания

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Introduction

Infrared photoelectronics of both special and dual applications is one of the high-tech and rapidly developing areas of modern optoelectronics. Of particular interest are studies on the creation of highly sensitive and high-speed detectors for the field of information technology, lidar flight time systems, quantum key distributions, remote sensing of gas, quantum optics, quantum computing and quantum communication applications [1].

Avalanche photodiodes (APD) are widely used in optoelectronics and communications to detect low-intensity signals. Avalanche photodiodes rely on amplifying internal multiplication by exploiting the effect of impact ionization as long as the electric field is large enough. Impact ionization makes it possible to generate several photon carriers, i.e., several electron-hole pairs are generated for one absorbed photon, which, in turn, makes it possible to amplify the light signal [2–3].

Due to the large asymmetry of the ionization coefficients of electrons and holes in silicon (Si), this material is very attractive for APDs [2]. However, silicon is not suitable for absorption at telecommunication wavelengths, which require the use of materials with a smaller band gap, such as germanium (Ge).

To eliminate many disadvantages, a useful alternative to these existing detection technologies is the use of Ge as an absorber in tandem with the Si multiplication layer. The Ge band gap provides effective absorption at wavelengths in the entire visible and infrared ranges up to a maximum wavelength of approximately 1600 nm at room temperature [3].

In recent years, with the development of weak signal detection technology, the research and application of single photon detectors (SPAD) has entered a new stage. To date, there are several types of photodetectors that can cope with the task of registering single photons with varying degrees of efficiency [4–5]: photoelectronic multipliers (PMT), avalanche photodiodes, superconducting nanowires.

APDs based on InGaAs/InP are commercially available and provide high-performance parameters for SPAD at wavelengths of 1.31 microns and 1.55 microns. However, they are much more expensive and incompatible with the integration of a complementary metal-oxide-semiconductor (CMOS) structure compared to silicon-based detectors. The lower cost of the technology may make it commercially feasible to expand the silicon APD based Ge/Si technology for infrared radiation [6–7].

Materials and Methods

In this work, planar structures of avalanche photodiodes based on Ge/Si with different thicknesses of the absorption layer and the multiplication layer were designed. Figure 1 shows a schematic cross-section and electric field distribution of the structure of an APD based on Ge/Si. These devices have a cylindrical shape with a diameter of 30 microns.

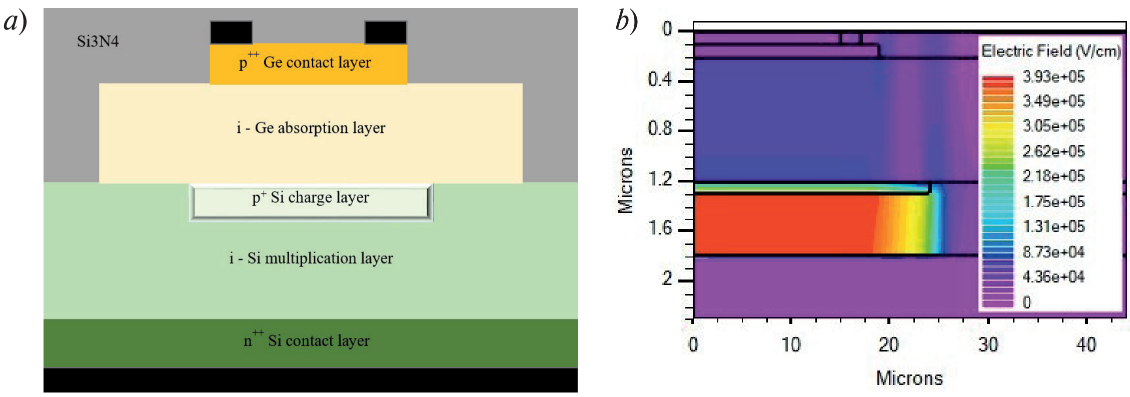

Fig. 1. APD based on Ge/Si cross section (*a*); Electric field distribution over the structure of an APD based on Ge/Si (*b*)

Typically, the average doping concentrations are controlled at the level of $\approx 1\times10^{20}$ cm^{-3} for the p^{++} contact, $\approx 1\times10^{17}$ cm^{-3} for the charge region and, respectively, $\approx 1\times10^{20}$ cm^{-3} for the n^{++} contact. In the APD structure with reverse voltage bias, the presence of a charge layer should ensure that the electric field in the Ge absorption layer is maintained below the APD breakdown field ($\approx 1\times10^5$ V·cm^{-1}) in order to avoid the tunneling effect, and in the Si multiplication layer is greater than the APD breakdown field ($\approx 3\times10^5$ V·cm^{-1}) to provide shock ionization [3–4].

The characteristics of the avalanche photodiodes were modeled using TCAD and simulated under an optical input power illumination of –20 dBm at 1310 nm. The program is based on three basic equations: Poisson's equation, continuity equations, and transport equations. Poisson's equation is related to the variations in electrostatic potential with local charge densities. The continuity and the transport equations address the transport processes, generation processes, and recombination processes of carriers.

During the simulation, avalanche photodiodes based on Ge/Si were compared with different thicknesses of Ge absorption layers (1 µm, 1.5 µm, 2 µm) and Si multiplication (0.5 µm, 1 µm, 1.5 µm) by gain, bandwidth and the product of gain by bandwidth, which significantly affect the operation of the device.

Results and Discussion

Figure 2, *a* shows the dependence of the multiplication (M) on the voltage for the APDs structures with different thicknesses of absorption and multiplication layers. To ensure a reliable comparison between the devices, the voltage ($V_{b\text{-}ref}$) is used – the difference between the breakdown voltage (V_{bd}) and the bias voltage (V_{bias}). As shown in Fig. 2, *a*, in linear mode, the gain of the APD 1, 2, 3 increases with a decrease in the multiplication layer. This is due to the distribution of the electric field in the multiplication layer, the larger the width, the smaller the electric field and the smaller the shock ionization [8]. In APD 3, 4 and 5 in linear operation mode, the gain decreases with increasing thickness of the absorption layer.

Figure 2, *b* shows the dependence of the bandwidth ($f_{3\text{-}dB}$) on the voltage for avalanche photodiodes based on Ge/Si with different thicknesses of absorption and multiplication layers.

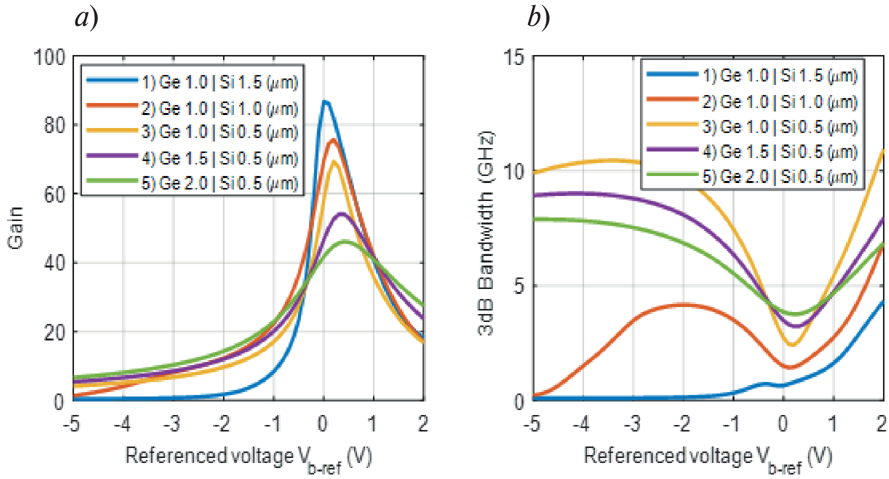

Fig. 2. Dependence of the gain of an avalanche photodiode based on Ge/Si on the thickness of the absorbing layer and the multiplication layer versus referenced voltage $V_{b\text{-}ref}$ (*a*) dependence of the bandwidth on the thicknesses of the absorption and multiplication layers versus referenced voltage $V_{b\text{-}ref}$ (*b*)

Conducting analyses between five APDs Fig. 2, *b* it can be concluded that APD 3 has a large bandwidth and the smallest thicknesses of the absorption and multiplication layers. For APDs structures 1 and 2, the electric field in the multiplication layer is lower than the breakdown field, thereby the carriers do not reach their saturation rates, so the drift time increases and the bandwidth decreases.

Thus, the bandwidth of the device is inversely proportional to the product of the thickness of the absorbing layer by the transit time of the carrier. A thinner absorbing layer can provide higher bandwidth, but it can also reduce sensitivity and increase noise levels.

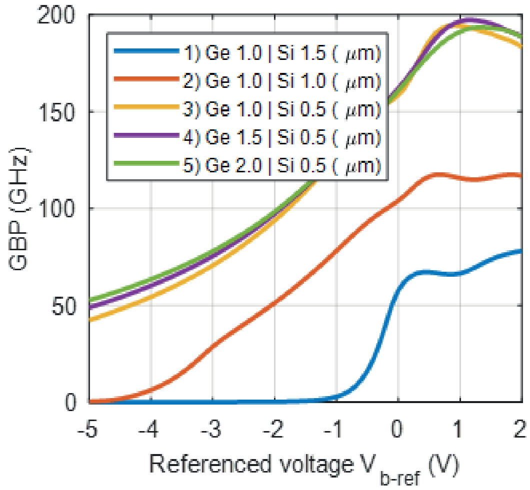

Fig. 3. GBP for five Ge/Si APDs with different thicknesses of absorption and multiplication layers versus referenced voltage $V_{b\text{-}ref}$

Figure 3 illustrates the gain-bandwidth product (GBP) for five avalanche photodiodes based on Ge/Si. The proximity of the GBP breakdown voltage for APDs 3, 4 and 5 is equal to ≈ 150 GHz. Comparing avalanche photodiodes 3, 4 and 5 in terms of gain and bandwidth in fig. 2, we see that these characteristics do not necessarily have to be high, it all depends on the operating conditions. GBP is a very important indicator for determining the effectiveness of an avalanche photodiode.

Before concluding this paper, it is worth noting that by utilizing simulation techniques, in TCAD to explore how the thicknesses of absorption and multiplication layers affect performance parameters like gain, bandwidth and gain-bandwidth product this study aims to provide valuable insights to the field. Understanding the relationship between these factors and performance outcomes is vital for developing APDs with functionality and efficiency. While it is true that other research articles have touched upon subjects it is important to emphasize the significance of this study for reasons. Firstly, the use of germanium on silicon APDs is gaining recognition within the optoelectronics community. Therefore, any progress or optimizations made in this area can significantly enhance the performance of the device. Secondly investigating absorption and multiplication layer thicknesses offers information for design optimization. By studying the impact of these parameters, researchers and device engineers can fine tune the APD structure to achieve gains, bandwidths and improved gain bandwidth products. This knowledge can be applied in fields such, as telecommunications, lidar systems and speed optical communications. Moreover, this study enables an analysis that provides an understanding of the underlying physics and mechanisms governing APD behavior.

Conclusion

In general, optimizing the thickness of the multiplication and absorption layers in APD requires a compromise between gain and bandwidth in order to balance the characteristics of the device. The dimensions that ensure the best performance will depend on the specific requirements for the device and operating conditions.

Thus, APDs 3 and 4 are the best option in terms of gain, bandwidth and gain-bandwidth product. The presented results of modeling the APDs parameters will serve to create experimental structures and study their practical parameters.

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