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Mushroom mesa structure for InAlAs-InGaAs avalanche photodiodes

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Mushroom mesa structure for InAlAs/InGaAs avalanche photodiodes (APD) was proposed and investigated. APD heterostructrures were grown by molecular-beam epitaxy. Fabricated APDs with the sensitive area diameter of about 30 micron were passivated by SiN deposition and demonstrated avalanche breakdown voltage Vbr 70-80 V. At the applied bias of 0.9 Vbr, the dark current was 75-200 nA. The single-mode coupled APDs demonstrated responsivity at a gain of unity higher than 0.5A/W at 1550 nm.

Keywords: avalanche photodiode, InAlAs/InGaAs, mesa structure, dark current.

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Avalanche photodiodes (APD) are widely used in optical telecommunication systems, laser radars and distance gauges, single photon detectors [1]. In the spectral ranges of 1310 and 1550 nm, APDs of the planar structure are now preferably used, which are based on InGaAs/InP heterostructures with separated absorption (InGaAs layer) and multiplication (InP layer) regions [2]. In such APDs, the $p-n$-junction regions are formed by local diffusion of the p-type dopant (typically Zn) into the weakly doped n-type InP layer [3]. An alternative approach is based on using heterostructures InAlAs/InGaAs in which an InAlAs layer is used as a multiplication region. As compared with InGaAs/InP-based APDs, the ratio between the electron and hole impact ionization rates is higher than the ratio between those of two carrier types in InP, which enables reduction of the avalanche multiplication noise level [4]. Besides this, the InAlAs impact ionization rates are less sensitive to temperature variations, which ensures better temperature stability of the breakdown voltage [5]. At the same time, InGaAs/InP-based APDs are characterized by very low dark currents, but this can be achieved by using a complex structure with protection rings and precise two-stage diffusion for suppressing the edge breakdown. In most versions of the InAlAs/InGaAs-based APD design, the lateral insulation of the device active region is performed by etching the mesa structure. In this case, the key problem is reduction of dark current, for instance, of the surface leakage current. For this purpose, various approaches are used: two-stage mesa etching with the surface passivation with benzocyclobutene [6] or polyamide [7], a combination of mesa etching and Zn local diffusion [8], three-stage mesa-structure [9]. The efficiency of the used approaches strongly depends on specific features of the heterostructure design that in its turn will be optimized so as to meet the requirements of specific applications.

This paper proposes and analyzes a version of a mushroom mesa structure of the InAlAs/InGaAs-based APD, which is formed by using selective etching.

The shape of the mesa-structure side wall significantly affects the APD characteristics. For instance, the multistage mesa structures were shown to ensure considerable reduction of the surface leakage currents. The mushroom shape of the mesa structure may be potentially interesting from the viewpoint of the surface leakage reduction, electric field redistribution with its concentration in the multiplication layer, and reduction of the $p-n$-junction parasitic area that does not reach the region of lightening in using the scheme involving radiation input through the front side where the p-contact metallization is located. To practically test the possibility of fabricating APDs with the mushroom mesa structure, in this study a concept of two-stage etching with non-selective and selective etchers has been used. The APD heterostructures were grown by the molecular beam epitaxy on substrates made from semi-insulating InP and consisted of strongly doped n-type InGaAs contact layer 800 nm thick, strongly doped n-type InAlAs layer 600 nm thick, undoped multiplication layer of InAlAs 850 nm thick, charged p-type InAlAs layer 75 nm thick, undoped InAlGaAs layer with the gradiently varying composition 75 nm thick, undoped absorbing InGaAs layer 1700 nm thick, undoped InAlGaAs layer with the gradiently varying composition 75 nm thick, strongly doped p-type InAlAs layer 75 nm thick, and a thin strongly doped p-type InGaAs contact layer. Relatively thick absorbing and multiplication layers a needed in using APD as a single photon detector [10].

Fabrication of APD crystals started from the formation of Ti−Pt−Au ring contacts, after which the mesa structure was etched in two stages. At the first stage, etching with H_3PO_4:HBr:$K_2Cr_2O_7$ (1:1:1) was performed under protection by a photoresist mask 40 μm in diameter with embedding into the strongly doped *n*-type InAlAs layer, the mesa top part size was $\sim 30\,\mu$m, and a circular groove was formed near the mesa outer edges (Fig. 1). In etching the second mesa, the photoresist mask outer edge was located close to the mesa structure wall outer edge so as to protect the structure side surface. The second stage of mesa etching was performed using etcher HCl:H_2O till opening the strongly doped *n*-type InGaAs contact layer over the entire area of the structure. At the same time, layers of InAlAs were slightly etched in the lateral direction. The SEM image of the edge profile of the obtained mushroom mesa structure is given in Fig. 2. Electron microscopic studies were performed using a scanning electron microscope JSM-7001F (Jeol, Japan) owned by the Federal Joint Research Center „Material science and characterization in advanced technology" (Ioffe Institite, Saint Petersburg). After that, the AuGe−Ni−Au ohmic contacts to the opened *n*-type InGaAs layer were made, insulating mesa structure was etched down to the InP substrate, windows in the strongly doped *p*-type contact layer of InGaAs were selectively etched, and characteristics of the APD were measured on the wafer. Then a SiN_x layer 190 nm thick was applied on the surface by the plasma-chemical deposition method; the layer thickness was compliant with translucence at the wavelength of 1550 nm. In the layer, windows with contacts of the *p*- and *n*-typewere opened, the surface was planarized with polyamide, and contact sites were formed. Characteristics of the fabricated APDs were selectively measured on the wafer prior to dividing into crystals using a probe station. In measuring photocurrent, laser diode ML976H6F-E01 with the 1550 nm spectral range was used as a source of radiation that was input into a multimode optical fiber. The studied photodiode was lightened through a lens formed at the fiber end and adjusted to the APD unity-gain maximum current. After that, the wafers were divided into crystals, and APD crystals were selectively assembled on holders with subsequent coupling with a single-mode optical fiber and measuring their unity-gain photo-responsivity. In this case, a single-mode coupled vertically irradiating laser was used as a radiation source, which allowed quantitative estimation of the optical power and lower value of the unity-gain photo-responsivity, since a portion of power is lost in the APD-fiber coupling.

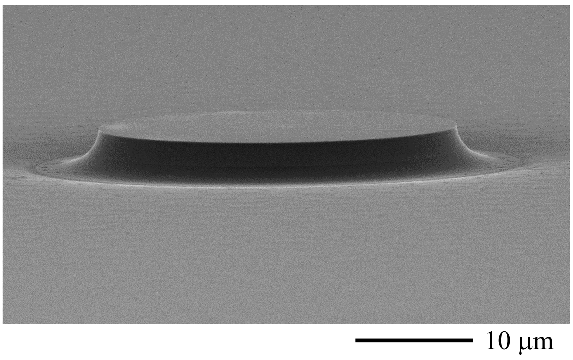

Figure 1. A scanning electron microscope image of the InAlAs/InGaAs-based APD mesa structure after the first stage of etching with a non-selective etcher H_3PO_4:HBr:$K_2Cr_2O_7$.

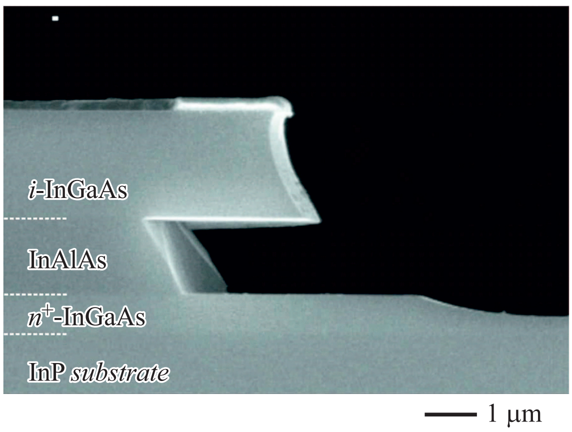

Figure 2. A scanning electron microscope image of the InAlAs/InGaAs-based APD mesa structure profile after the second stage of etching with a selective etcher HCl:H_2O.

Fig. 3 presents the measured dependences of dark current and photocurrent on the applied bias for one of the fabricated InAlAs/InGaAs-based APDs with the mushroom mesa structure. The same figure demonstrates the dependence of the avalanche multiplication factor calculated from the experimental data. As shown by the results of similar measurements carried out for a large sample of crystals on a wafer, the fabricated APDs exhibit breakdown voltages ranging from 70 to 80 V and dark currents of 75−200 nA at the applied bias of 90Such dark currents fare worse than the best published data, which may be caused by a non-optimized technique of the mesa structure surface passivation and non-optimal doping level of the charged *p*-InAlAs layer. Prior to passivating with the SiN layer, the measured dark currents of the best APDs made from the same heterostructure were 20−40 nA under the same experimental conditions.

APDs with separated regions of the carrier absorption and multiplication are characterized by the dark current variations and initiation of the efficient photo-responsivity when the breakdown voltage is reached and the depletion region extends beyond the avalanche multiplication layer into the absorption layer. The fabricated APDs exhibit such a behavior at voltages of about 20−25 V. To refine the breakdown voltage value, voltage-capacitance characteristics of the test diodes formed in the vicinity of the operating ones were measured. Fig. 3 presents one of the measured voltage-capacitance characteristics having a characteristic step at the voltages of 20−23 V, which correlates well with the dark current measurements.

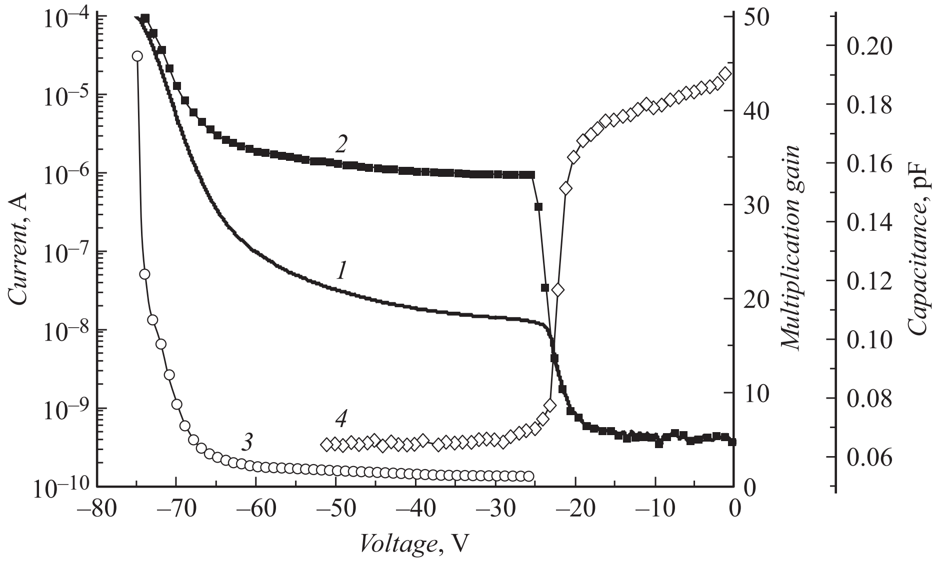

Figure 3. Characteristics of the InAlAs/InGaAs-based APD with the mushroom mesa structure: dark current (*1*) and photocurrent (*2*) versus the applied bias; the corresponding dependence of the avalanche multiplication factor (*3*); the voltage-capacitance characteristic of the test diode (*4*).

Measurements of single-mode coupled APD crystals showed the unity-gain photocurrent of 1350−1400 nA at the laser radiation power in the fiber of 2.6 μW, which provides the minimal photo-responsivity estimate of about 0.54 A/W.

The proposed version of the mushroom mesa structure formed by using selective etching enabled fabrication of the InAlAs/InGaAs-based APDs with the photo-sensitive region diameter of $\sim 30\,\mu$m, breakdown voltages of 70−80 V and dark currents of 75−200 nA at the applied bias of 90% of the breakdown voltage after the surface passivation with the SiN layer. The unity-gain photo-responsivity exceeds 0.5 A/W in case of the single-mode coupling. Optimization of the heterostructure design and the APD fabrication technique, for instance, passivation of the mushroom mesa structure surface, can essentially improve the APD characteristics.

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Conflict of interests

The authors declare that they have no conflict of interests.

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