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A new (CdHg)Te Photodiode Type with Protected Junction Surface

A new type of heterostructural graded gap (CdHg)Te photodiode with protected junction surface has been proposed. The photodiode was constructed with the use of (CdHg)Te epitaxial layers with alloy composition gradient. Photoelectrical and current-voltage characteristics of the obtained p-n junctions were measured. It has been shown that the described type of photodiode creates a possibility to perform stabile and resitant against external influences parallelly with high performances infrared detectors for the wavelengths in the range (1-15) μm.

1. Introduction

(CdHg)Te photodiodes are used as fast and sensitive infrared detectors in the wavelength range (0.0–30) μm. The first photodiodes were obtained by diffusion of mercury into p-type (CdHg)Te (1–3). Very high values of normalized detectivity were obtained also for p-n junctions fabricated with the use of implantation technique (4–6). The application of epitaxial layers technique simplified considerably the p-n junction technology and enabled the fabrication of multielement detector arrays with large surfaces (7–8). Another important problem is related to elaboration of photodiodes with better stability. In consequence of low melting point of (CdHg)Te, high diffusion coefficients of impurities in this material and relatively high value of mercury pressure lead to the situation in which photodiodes become highly sensitive to both the ambient athmosphere and variations of temperature (9–10). The region of a particular sensitivity with respect to the mentioned above factors is the p-n junction surface. The main reason of instabilities in the operation of the photodiodes are surface leakage currents. The passivation of the p-n junction regions with the use of protecting layers proved to be not effective because of the mechanical strains which being generated at the interface in the course of cooling, lower the parameters of the p-n junctions and usually destroy the protection layers. A good protection of the p-n junction against surface breakdown is indispensable especially when high reverse voltages are involved, in order to decrease RC time constant and obtain short photoresponse time.

An actual and important problem to be solved for the usage of photodiodes for application in the range of far infrared radiation is the preparation of p-n junctions with internal quantum gain because of charge carrier multiplication occurring in the space charge region (avalanche photodiodes). Avalanche carrier multiplication is possible in case of 10.6 μm photodiodes working at near liquid nitrogen temperature (2). Avalanche photodiodes should be well protected against electrical surface breakdown. In the case of semiconductors with wide energy gap this is realized by applying a guard ring technique. The application of this technique rises some difficulties when the material with narrow band gap are used, because of the reverse current increase due to leakages at weaker doped guard ring region. For these reasons a new method of the junction edge protection in graded gap structures has been proposed and realized. This method allows the localization of the p-n junction boundary in a region with band gap wider than that of the region which for a given wavelength range is the most important.

In the present paper the results of the investigations of the p-n junction prepared by means of this technique are given and discussed.

2. p-n junction technology

The structures with alloy composition gradient were obtained by isothermal (550–600)°C deposition of HgTe onto CdTe wafers, lasting

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several days. In this way layers (100–500) μm thick were obtained.

The alloy composition of the layers varied continuously from CdTe to HgTe.

The (CdHg)Te layers and CdTe plates about 50 μm thick being cut off from the CdTe substrate wafers were sliced into small about $1 \times 1\ mm^2$ plates. Thereupon in each plate conical hollows have been made on CdTe surface. The hollows can be made by mechanical methods or by selective etching. In the course of further stage the layers about 20 μm thick were removed from each surface of the structure due to etching in bromine-methanol solution. After etching the samples were carefully washed in methanol and subjected to the mercury diffusion process. The diffusion was carried out in saturated mercury vapour at (250–400)°C and during (10–60) min.

In the course of diffusion n-type layers were formed on all but CdTe surfaces of the sample. The electrical connections were made by the deposition of metal layer. Metal was deposited by several methods, e.g. by chemical deposition of gold from chlorine-gold acid, electrochemical deposition of indium, vacuum evaporation of In, Al, Au and so on to obtain finally photosensitive element shown in Fig. 1.

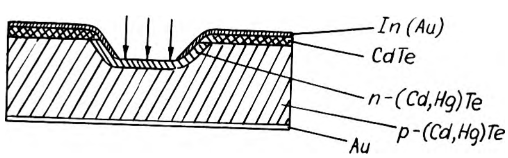

Fig. 1. Cross-section of the photodiode — version A

A photosensitive element with flat frontal surface could be also obtained. In this case HgTe was deposited onto CdTe in which the hollow was made previously. The remaining technological details were similar to the ones described above.

Figure 2 presents the cross-section of the photoelement obtained by the latter technique. The described technique is more suitable for production of one or two dimensional detector arrays due to the surface flatness.

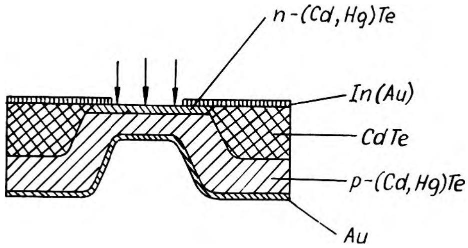

Fig. 2. Cross-section of the photodiode — version B

In photodiodes produced by means of both methods the p-n junction edge is located in the region with increasing CdTe contents, hence, in material with increasing band gap value.

It has been found that the diffusion of mercury did not cause the formation of n-type surface layer in CdTe.

3. Current-voltage characteristics

To obtain a desired shape of I–V characteristics, that electrical contacts should be made properly. The preparation of electrical contact to p-type region is relatively simple. This region has a large area and its alloy composition approaches the HgTe one. The existence on n-type layer below this area, does not exert any influence, because for a junction in semimetals its electrical characteristics are linear and resistance is very low. Low-resistance contact can be prepared by means of any method mentioned before. The preparation of the electrical contact in n-type region displayed greater difficulties. Low-resistant contacts could be obtained by chemical deposition of gold only in case of the p-n junctions sensitive to waves longer than 4 μm. Fig. 3 shows the influence of contact preparation on diode current voltage characteristics.

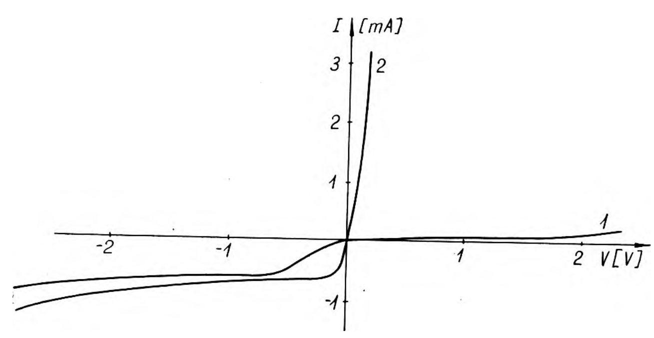

Fig. 3. Current-voltage characteristics of the photodiodes with different contact materials to n-type layer

1 — electroless gold; 2 — electroplated indium, $A = 1 \cdot 10^{-3}\ cm^2$; $\lambda_{0.5} = 3.5\ \mu m$; $T = 300\ K$

The most difficult task was to prepare low series resistance for the p-n junctions sensitive to the (0.8–2) μm wavelengths range. In this case n-type layers were characterized by relatively high values of sheet resistance. Nevertheless satisfactory results could be obtained if electrochemically deposited indium contacts were prepared with configuration shown in Fig. 4. This allowed to obtain the diodes with series resistances of the order of several ohms.

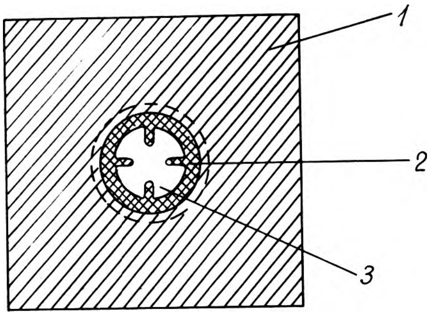

Fig. 4. Front surface view of the photodiode
1 – indium electroplated CdTe; 2 – indium electroplated (CdHg)Te; 3 – sensitive area

The shape of current-voltage characteristics was determined by the junction properties within the region of the smallest band gap value, i.e. at the bottom of the conical hollow. The value of band gap could be controlled by changing the hollow depth. Because of the fast increase of the band gap, the edge region of the p-n junction gives only a small contribution to the reverse current. At the same time, it has been found that in regions of both p and n types the majority carrier concentration decreases with the increase of band gap value. In this way the value of the space charge width is the smallest in junction region with the smallest energy gap. Hence, it follows that the edge regions of the junctions are highly protected against surface electrical breakdown. In Fig. 5 the examples of current-voltage characteristics of the p-n junctions are shown. Like in the case of the p-n junctions prepared by means of other techniques [7–8], the shape of the reverse characteristics is the functions of the spectral range and temperature. The characteristics obtained for the junctions cooled to 77 K had no saturation region. The characteristics with saturation region being obtained at about 200 K for p-n junctions sensitive for wavelengths range (4.5–10) μm. For junctions working at room temperature with the maximum sensitivity within wavelengths range 0.8-2 μm, the characteristics obtained were without saturation region; this region being observed for wavelength

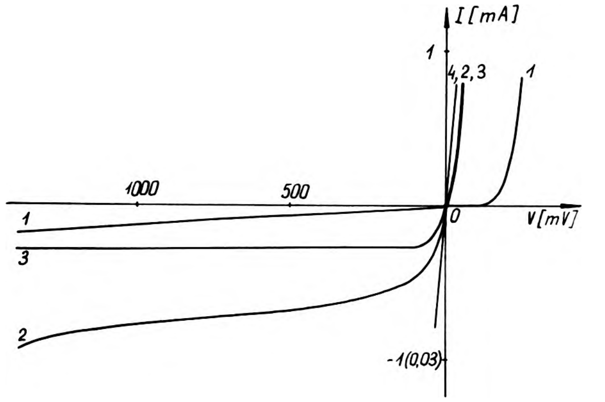

Fig. 5. Examples of current voltage characteristics of the photodiodes
1 – $\lambda_{0.5}$ = 5.2 μm, T = 80 K, A = 0.12 mm²; 2 – $\lambda_{0.5}$ = 10.6 μm, T = 80 K, A = 0.08 mm²; 3 – $\lambda_{0.5}$ = 3 μm, T = 300 K, A = 0.10 mm²; 4 – $\lambda_{0.5}$ = 5.5 μm, T = 300 K, A = 0.20 mm². Value in bracket refers only to the reverse branch of curve 1

3–4 μm. For waves longer than 5 μm – the characteristics were linear. The changes of the shapes of reverse characteristics are due to the changes in generation and diffusion of minority carriers occurring in space charge region. The generation equilibrium of minority carriers prevailing initially the diffusion with the growth of minority carrier concecration is overdominated by the diffusion of carriers from the outside of the space charge region. In the case of high concentration of minority carriers the junction resistance is lower than that of electrical connections. That is why linear characteristics are observed experimentally.

4. Photoelectrical characteristics

The spectral form of photovoltaic characteristics depends mainly on the junction region with the smallest band gap. The latter could be regulated by changing the conical hollow depth. Within short waves the spectral characteristics depend also on the distance from illuminated surface to the junction boundary. In case of shallow junctions the shape of spectral characteristics was approximately similar to the ideal photon counter, selective characteristics being observed for deep junctions.

The observed shapes of characteristics can be explained by the following reasons. Due to the short wave radiation the carriers are generated in thin n-type layer and nonequilibrium holes diffuse to the junction region. In the case of shallow junctions majority of carriers reaches the junction region. In the case of deep junctions the carriers mainly recombine before they reach the junction. Within wavelengths near the maximum of the photosensitivity the radiation generates carriers in the immediate neighbourhood of the junction, in this case the carriers are well collected by the contact field independently of the thickness of n-type region.

The spectral form of the characteristics, e.g. their selectiveness, could be changed by changing the distance of junction to the surface (Fig. 6). In the range of long wave tail the photosensitivity decreased only slightly. The

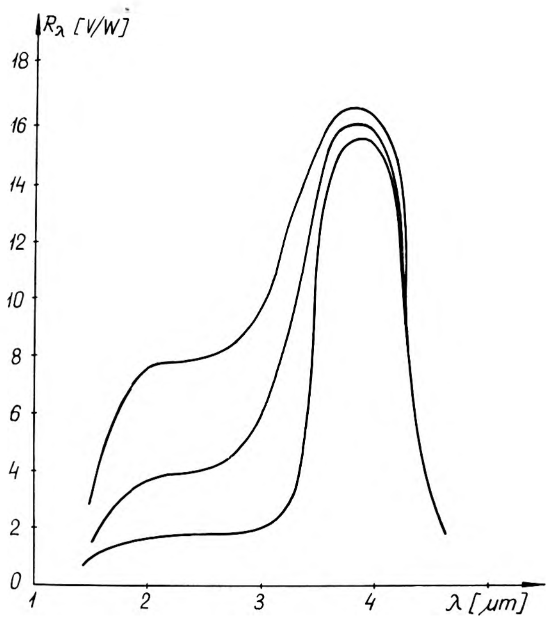

Fig. 6. Spectral characteristics of the photodiode in the dependence on junction depth $T = 300$K
1 – initial characteristics; *2* – after surface layer 11 μm thick was etched off; *3* – after surface layer 23 μm thick was etched off

latter shows that long wave radiation is relatively weakly absorbed in n-type region located near the illuminated surface. This effect may be due to the existence of band gap gradient or / and Burstein effect. The energy gap decreased from the surface toward the junction and absorption in n-type region would decrease due to Burstein effect.

In the short wave part of the spectral characteristics the existence of local flat dependence of I–V characteristics was observed. These flat parts both for deep and shallow junctions, were observed independently of the properties of the surfaces investigated. It seems that the existence of short wave flat parts of I–V characteristics originates from the growth of quantum yield, probably due to carrier multiplication (11).

It has been found that considerable growth of photosensitivity up to several hundred times due to the reverse bias can be obtained. A sharp and asymmetric maximum of the photoelectrical sensitivity depending upon the reverse bias was usually observed. This maximum overlapped the maximum of p-n junction differential resistance in a way similar to that in case of the junctions obtained due to diffusion of gold (12).

In the case of p-n junctions with the sensitivity maximum in (3–14) μm wavelength range and working at liquid nitrogen temperature, the current generated by background radiation at room temperature for 30–180 °FOV was usually much higher than the junction dark current. In the latter case, by applying relatively small reverse bias to compensate the photovoltage generated by background radiation, a considerable increase in photosensitivity and detectivity could be obtained. As an example the parameters of several photodiodes are given in Table 1.

Table 1

λ μm	Work temperature K	Background temperature K	FOV°	Photosensitive area mm²	Detectivity $D^* \cdot 10^{10}$ cm $Hz^{1/2}W^{-1}$	Remarks
2	300	300	180	0.1	2.6	Detectivity limited by electronics equipment noise
3.5	300	300	180	0.1	1.1	
3.0	300	300	180	0.05	0.4	
3.5	300	300	180	0.05	0.11	
4.0	300	300	180	0.03	0.03	
5.2	80	300	60	0.1	30	Reverse bias was applied to compensate background photovoltage
6.3	80	300	60	0.1	18	
5.2	80	80	0	0.1	90	Detectivity limit determined by Johnson noise
6.3	80	80	0	0.1	65	

5. Investigation of the stability of the p-n junctions

The changes of the junctions properties were investigated for thick n-type layer sensitive within wavelength range (1.5–12) μm. The investigations have shown that no measurable changes occur in the spectral and current-voltage characteristics of the junctions after

1. Keeping in air or in vacuum for more than three months.

2. Annealing in air or in vacuum at 100°C for about five minutes.

3. Rinsing in water.

4. Washing in different organic solvents e.g. in methyl and ethyl alcohols, in benzene, acethon, ether etc.

6. Final remarks

The carried out investigations have shown that the described technology is suitable for preparation of highly sensitive, photovoltaic infrared detectors with high detectivities. These detectors are more resistant to external factors than the usual mesa type p-n photodiodes.

The investigations on the detailed properties of these junctions within the range of high reverse bias, and on the possibility of avalanche multiplication of carriers are continued.

Новый тип фотодиода (Cd Hg) Te с защищенной поверхностью перехода

Предложен новый тип гетероструктурного фотодиода с защищенной поверхностью перехода. Фотодиод был построен при использовании эпитаксиальных слоев (CdHg)Te с градиентом состава сплава. Измерены вольтамперные характеристики электронно-дырочных переходов. Показано, что фотодиоды этого типа позволяют строить детекторы инфракрасной области, устойчивые и стойкие к внешним влияниям, обеспечивающие доброкачественную работу для диапазона длин волн 1-15μм.

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