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Physical Principles of Photocurrent Generation in Multi-Barrier Punch-Through-Structures

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1. Introduction

The reach-through effect representing close up the space charge regions of two adjacent oppositely biased junctions leads to a sharp exponential increase in current from the bias voltage (Sze et al., 1971). Therefore, this effect was originally found in transistor structures was undesirable. But in the further development of electronics, this effect has found many applications in electronic devices. For example, in barrier injection transit-time diodes as dc-current bias (Chu & Sze, 1973; Coleman & Sze, 1971; Presting et al., 1994), in static induction transistors as an extra advantageous current to increase the transconductance of the transistor (Nishizawa & Yamamoto, 1978), in low-voltage transient voltage suppressors as a clamp device (de Cogan, 1977; King et al., 1996; Urresti et al., 2005), in JFET optical detectors as a reset mechanism (Shannon & Lohstroh, 1974, as cited in Lohstroh et al., 1981), in IGFET tetrodes as a modulated current flow (Richman, 1969, as cited in Lohstroh et al., 1981), in punch-through insulated gate bipolar transistors (Iwamoto et al., 2002), in gate-field-controlled barrier-injection transit-time transistors and in light injection-controlled punch-through transistors (Esener & Lee, 1985).

Due to the predominance the diffusion processes in structures with reach-through effect (Lohstroh et al., 1981; Sze et al., 1971) characters of the generation-recombination processes in the space charge regions in these structures, as well as non-stationary processes caused by extraction of the majority carriers and formation of the uncompensated space charge in the base layer are still remain unexplored. To prevent the diffusion processes three-barrier structure was developed, in which the flow of both types of carriers in the structure is limited by rather high potential barriers (Karimov, 1991, 1994, 2002). This allowed us to research in such structures the generation-recombination processes in the space charge regions after reach-through, as well as the influence of illumination on these processes. In these structures is found the internal photocurrent gain (Karimov & Karimova, 2003; Karimov & Yodgorova, 2010), which can not be associated with an avalanche or injection processes. Thus, this section is devoted to disclosing the mechanisms of charge transport and the nature of the internal photocurrent gain in multibarrier reach-through-photodiode structures.

In this section, is given a brief overview of multibarrier photodiode structures, as well as the results of a comprehensive research of the dark and light characteristics of multibarrier reach-through-photodiode structures. On the basis of which is proposed model, which explains the mechanism of charge transport and internal photocurrent gain, as well as some future trends.

2. An overview of multibarrier photodiode structures

The sensitivity and the bandwidth of the photodetector is critical to the overall performance of the receiver. A higher sensitivity translates into a longer distance possible between the last repeater and the receiver, without loss of data. The bandwidth of the photodetector will define the overall upper bandwidth limit of the receiver. There are two major types of the photodetector used in the telecommunication systems today – a p-i-n photodiode and an avalanche photodiode. The sensitivity of the p-i-n photodiode by itself is often too low for long-haul applications, typically, as the bandwidth is increased, the sensitivity is decreased. The alternative to the p-i-n photodiode, the avalanche photodiode, improves the sensitivity of the p-i-n photodiode by an additional section of the chip (section with high enough electric field for the formation of the avalanche multiplication) that provides gain. Depending on the gain of the device the sensitivity can be varied over a few dB without severe penalty in the bandwidth of the device. However, there is an additional noise associated with the gain section of the device which will impact receiver sensitivity. Also, at high gains, the device bandwidth will be limited by the gain-bandwidth product (a typical value of this product is 100 GHz). A typical operating current gain of the gain section of the device is 3 to 10 without penalty in the device bandwidth. In this rang the device is usually RC-limited. One of the first multibarrier structures with internal photocurrent gain is a bipolar phototransistor (Campbell, 1982). A phototransistor can have high gain through the internal bipolar-transistor action, which was significantly improved by utilizing a wide-gap emitter (Chand et al., 1985), or by utilizing punch-through transistors (Esener & Lee, 1985). It should be noted that the inherent to transistors large areas degrades their high-frequency performance.

Semiconductor device with two metal-semiconductor rectifying junctions can also be attributed to multibarrier photodiode structures (Sugeta & Urisu, 1979). In these structures, high performance is ensured by non injecting metal-semiconductor junctions and low capacitance of planar barriers. Non injecting nature of the metal-semiconductor junction suppresses internal photocurrent gain. Presence of the carrier injection in one of the junctions allowed one to obtain photocurrent gain for low-frequency range. Internal photocurrent gain in the high-frequencies has been achieved only when avalanche multiplication is present. However, in case of variation of the parameters of the potential barriers may cause some amplification of the primary photocurrent. The mechanism of the observed internal photocurrent gain can be attributed to the formation of a nonuniform electric field distribution and the separation of light-generated carriers near the anode with simultaneous additional emission of electrons from the cathode (Klingenstein et al., 1994). However, the use of series-connected heterojunctions and metal-semiconductor junctions allows one to control the spectral range of responsivity.

Series connection of the three barriers to longer enough short base layers allows one to obtain the internal photocurrent gain as a photothyristor. However, it is having the S-shaped current-voltage characteristic leads to instability of its parameters, and therefore can only be used as an optical switch. By serial connection of the p-n-junction with a high resistive long-base layer were obtained the injection-based photodiodes whose characteristics are similar to photothyristor characteristics (Vikulin et al., 2008). At the same time these photodiodes are had sufficient internal gain in the prebreakdown region, but decreased high-frequency performance.

Thus, in most multibarrier photodiode structures are inconsistent the high-frequency performance and the photosensitivity, i. e. there is a competitive relationship between them, which leads to the constancy of their product. In this aspect, it would be appropriate to create a new class of multibarrier photodiode structures that is an alternative to avalanche photodiodes and field phototransistors.

3. Three-barrier reach-through-photodiode structure

Investigated a three-barrier reach-through-photodiode structures on basis of gallium arsenide were produced on base of technology for obtaining abrupt p-n-junctions from epitaxial homolayer or heterolayer p(n)-type which was growth from a liquid phase on substrate n(p)-type (we used a substrates doped with shallow or deep impurities). The carrier concentration in the grown epi-layer (with thickness 1-2 microns) was $5\text{-}7\cdot 10^{15}$ cm^{-3} and in the substrate $1\text{-}9\cdot 10^{15}$ cm^{-3}. By evaporation in a vacuum of the translucent layers Ag (70 Å) on both surfaces of structure were obtained rectifying junctions (in some samples to obtain the barrier was used Au). Height of potential barriers were measured by a photoelectric method are 0.6-0.8 eV and are determined by fixing the Fermi level on surface states. As a result, were made three barrier m_1-p-n-m_2-structures with an area of 2-25 mm^2, in which m_1-p- and n-m_2-junctions are physically connected in series, and p-n-junction opposite. Due to the existence of a blocking junction at any bias polarity these structures are able to operate at both polarities of the bias voltage and a double-sided sensitive, i. e., the photocurrent can be taken under illumination from either side of structure. The total capacitance of the structure is close to the value determined by the geometric size of the entire structure and is about 0.2-0.5 pF/mm^2.

The proposed structure is similar to a thyristor, but differs from it in the larger thickness of one of the base regions (the thickness of the n-region is equal to 350 microns), while in the thyristor three barriers are separated by two base regions with a thickness, which is in one order with the diffusion length of minority carriers (Sze & Kwok, 2007). In this case, the smaller thickness of other base region contributes to close up the space charge regions of adjacent junctions before the onset of avalanche multiplication.

4. The dark characteristics

Investigated m_1-p-n-m_2-structure in the initial bias voltages has typical current-voltage characteristics for a structure with three successively connected barriers (i. e. the current transport is determined by the reverse-biased junctions and in the case of the generation mechanism the dependence is a power law with an index equal to 0.5), which are then in voltages above a certain voltage (U_o) changed to a linear dependence as resistors, Fig. 1. In this case, the resistance was determined from the slope of current-voltage characteristics is several orders of magnitude higher than determined by resistivity and the geometric sizes of the base regions, which indicates the existence of potential barriers in the modified structure. However, the observed linear character of current-voltage dependence can not be explained within the existing theories of the barriers.

The observed behaviors of the current-voltage characteristics are associated with the effects taking place in a three-barrier structure when the voltage is increased beyond the reach-through voltage. As is well known for reach-through-structures charge transport through these structures is determined by the minority carriers (in our case electrons) that are emerging from the forward-biased junction. However, in the m_1-p-n-m_2-structure the metal-semiconductor barriers restrict the flow of these carriers. Thus, in a three-barrier reach-through-structures the current density through the structure after the reach-through is determined by double-sided thermal electron emission, i. e. the flow of holes is limited by the left barrier, while the flow of electrons is limited by the right barrier.

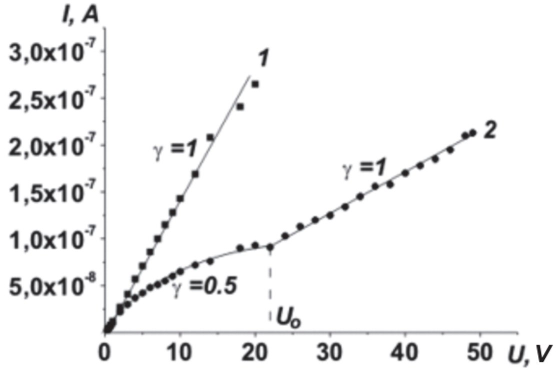


Fig. 1. Measured *I-V* characteristics of the three barrier structure at opposite bias polarities: 1 - (+)m-p-n-m(-); 2 - (-)m-p-n-m(+); γ – power index in $I \sim V^{\gamma}$.

In case of forward biased p-n-junction in the initial bias voltages the space charge regions of the metal-p and p-n-junctions are closed up which is caused by sufficiently thin base-layer. In the further increase of bias voltage the energy bands of the p-n-junction tend to become flat, which leads to a significant increase in current density of electrons from the n-region, Fig. 2. According to the research (Sze et al., 1971), the current density of electrons from the n-region is defined by:

$$j_n^{p-n} = A_n^* T^2 \exp\left(-\frac{q\left(V_{FB} - V\right)^2}{4kTV_{FB}} \right) \tag{1}$$

It should be noted that the current density of electrons incoming to the n-region is limited by the potential barrier of the n-metal-junction:

$$j_n^{m-n} = A_n^* T^2 \exp\left(-\frac{q\varphi_{m-n}}{kT} \right) \tag{2}$$

Therefore, in the n-region adjacent to the p-n-junction there is a strong depletion of the major carriers, which leads to the formation of an uncompensated positive space charge of ionized donors, which in turn attracts electrons from the nearby area leading to the formation of new uncompensated positive space charges, which contributes to the further development of non-stationary processes in n-region. These processes will continue until the establishment of equilibrium between the currents of electrons emerging from the n-region and incoming to the n-region. The required reduction in current density of electrons emerging from the n-region is given by the decreasing of equilibrium concentration of electrons in the n-region, which, while maintaining electrical neutrality of structure becomes possible when the donors go to the neutral state. The conductivity of the n-region becomes close to intrinsic conductivity, which leads to an increase in its resistivity and an increase in the incident in this area bias voltage. As a result, the current-voltage characteristic of the structure becomes close to linear. The degree of depletion of the n-region and thus its resistivity determines by the current density of electrons through the n-metal junction:

$$R_{n-region} = f\left(j_n^{m-n}\right) \tag{3}$$

In case of reverse biased p-n-junction in the initial part of the current-voltage characteristics the dependence is a power law with an index equal to 0.5, which is due to the predominance of the generation processes in the space charge region of reverse biased junction. Above a reach-through voltage the energy bands of the metal-p-junction tend to become flat, which leads to a significant increase in current density of holess from the p-region, which leads to the formation of an uncompensated negative space charge of ionized acceptors. Field of space charge reduces the built-in potential of the n-metal-junction, leading to an increase in current density of electrons overcoming the barrier of n-metal while the current density of electrons incoming to the n-region is limited by barrier metal-p. As a result, just as in the above case, we have depleted n-region. Thus, the current-voltage characteristic of the structure is changed to a linear one. The degree of depletion of the n-region and thus its resistivity in this case are determined by current density of electrons through a metal-p:

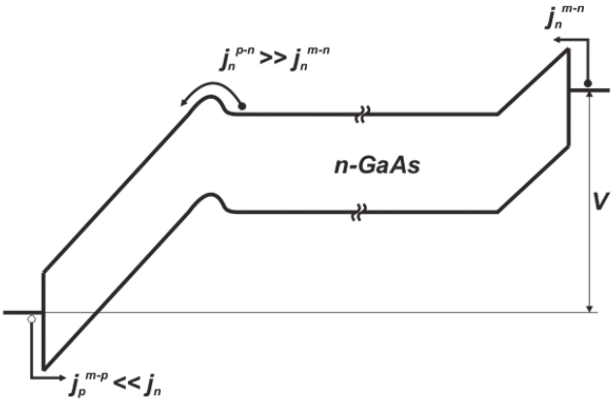


Fig. 2. Energy band diagram of a three barrier structure at bias polarity (+)m-p-n-m(-) after reach-through.

$$R_{n-region} = f\left(j_n^{m-p}\right) \tag{4}$$

Thus, for both polarities the current transport is determined by an identical mechanism. Due to the fact that the barrier height of metal-p-junction is greater than the barrier of n-metal-junction resistance of the structure in the mode of blocking of the p-n-junction is of greater than another mode.

Temperature dependence of the resistance of the structure in the linear region in both modes is described by the function (Fig. 3.)

$$R_C T \propto \exp(f(\frac{1}{T})) \tag{5}$$

As noted above the current flowing through the structure is determined by the resistance of the depleted n-region, which in turn depends on the intrinsic carrier concentration in this region and current density of electrons through the n-metal- (or metal-p-) junction, which explains the existence of two linear regions with different slopes in this relationship. Activation energy determined from these slopes at low temperatures corresponds to the energy band gap, and at high temperatures to the potential barrier's height. Accordingly, the change in slope with increasing the temperature is caused by prevalence of the thermionic electron current through the metal-semiconductor junction for high temperatures.

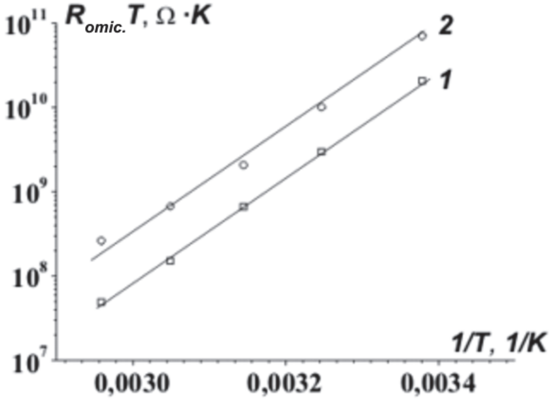


Fig. 3. The resistance of the three barrier structure as a function of temperature at opposite bias polarities in linear region of *I-V* characteristics: 1 - (+)m-p-n-m(-); 2 - (-)m-p-n-m(+)

Temperature coefficient of voltage break point of the current-voltage characteristic has a negative value with a coefficient of -0.098 V/K, so we can assume that the break point is uniquely determined by the reach-through of adjacent junctions of the structure.

Thus, despite the fact that the structure contains a number of series-connected barriers at voltages higher than a reach-through voltage its current-voltage characteristic becomes linear.

5. Light characteristics

Consideration of the structures in the photovoltaic mode, showed that in structure is generated the photo-EMF. The dependence of short circuit current on the intensity of light is nearly linear. Load characteristics in accordance with the current-voltage characteristics are linear, which leads to increased half-width of the maximum output power.

Light characteristics taken from the integral lighting (incandescent lamp) at 100 lux are shown in Fig. 4. In this figure solid line represents the data of the reference photodiode (single-barrier p-n-photodiode) without internal gain. For the researched structures at both polarities of the bias the photocurrent increases with bias voltage to much greater values than in the reference photodiode indicating the presence of internal photoelectric gain. In the reverse-biased p-n-junction at low voltages is taken a tendency to saturation of the photocurrent, as in conventional photodiode without amplification, but when the voltage is increased beyond the reach-through voltage the photocurrent begins steady with voltage.

Curves of light characteristics in case of forward-biased p-n-junction under illumination by side of the p-type layer with increasing light intensity move in parallel toward higher currents. This can be explained by the fact that from the light emission increases the current density of electrons to the depleted n-region through the n-metal-junction, which leads to a decrease in the degree of depletion and resistance of this region

$$R_{n-region} = f\left(j_n^{m-n}\right) = f\left(j_{dark}^{m-n} + j_{photo}^{m-n}\right) \tag{6}$$

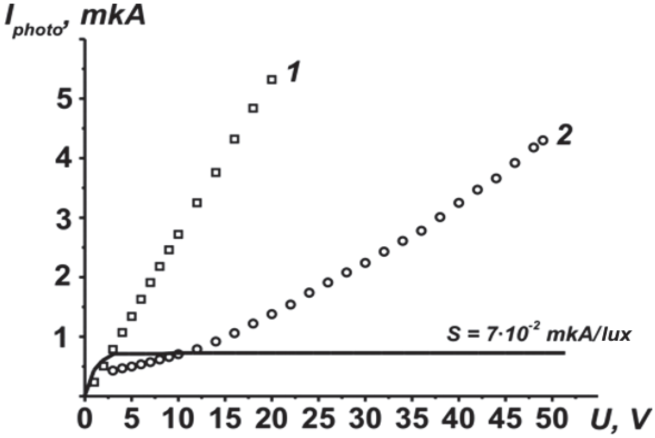


Fig. 4. Photocurrents of the three barrier structure and reference photodiode as a function of bias voltage at opposite bias polarities: 1 - (+)m-p-n-m(-); 2 - (-)m-p-n-m(+)

It is known that the light with energy in the region $\varphi < h\nu < E_g$, which is absorbed in the metal and excites photoemission of electrons from this metal is not absorbed in the bulk of the semiconductor, so changing the illuminated area does not affect the sensitivity of the photodiode.

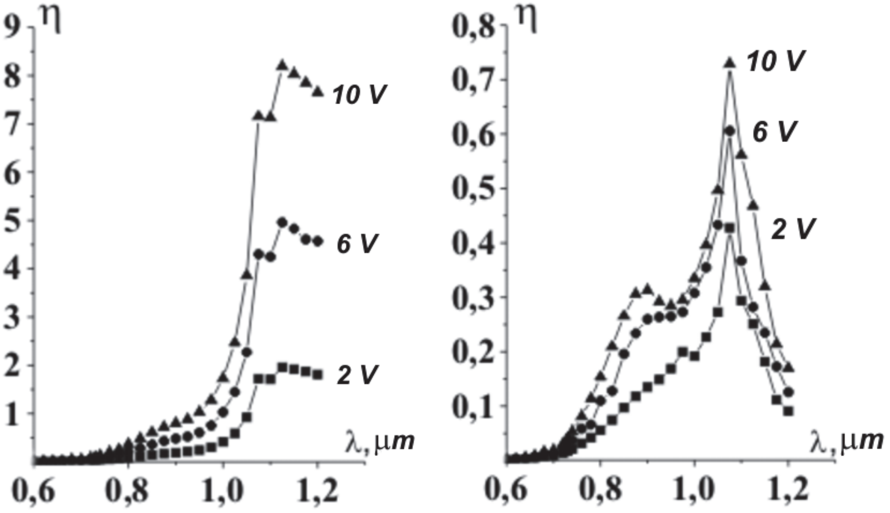
Analysis of the spectral response of the three-barrier reach-throuch-structure (Fig. 5.) shows that in the both polarities of the bias and regardless from the illuminated surface (top or bottom surface) the photosensitivity is higher when the absorbed light excites photoemission of electrons from the metal than the case when the absorbed light excites intrinsic photogeneration. This agrees well above given mechanism of photosensitivity and due to the fact that the resistance of the depleted n-region is determined only by the current density through the metal-semiconductor junction.

It should be noted that in all the structures external quantum efficiency was greater than unity and indicates the presence of internal gain in these structures. In this case, the observed internal photocurrent gain in the structures does not fit into the framework of the avalanche and the transistor (injection) effects.

6. Mechanism of the internal photocurrent gain

The mechanism of charge transport, depending on the polarity of the operating voltage practically does not differ, which leads to the identity of the internal photocurrent gain in both modes, so we restrict ourselves to the case for direct mode, i. e. forward-biased p-n-junction mode.

In the forward-bias p-n-junction mode because of the narrowness of the p-region metal-p junction and p-n-junction interlock quickly, which leads to an exponential increase in current density of electrons from the n-region with the approach of the bias voltage to flat-band voltage. In this case, the current density in the n-region is limited to the saturation current density of n-metal junction. Since $j_n^{p-n} >> j_n^{m-n}$, the n-region is depleted of electrons, which leads to an increase in resistance of this region. Depletion of electrons continues until the current density of electrons emerging from the n-region decreases did not reach a current density of electrons incoming to the n-region. Thus, the degree of depletion is determined by current density of electrons incoming to the n-region.



a) b)

Fig. 5. Spectral response of the three barrier structure at opposite bias polarities and different bias voltages: a) (+)m-p-n-m(-); b) (-)m-p-n-m(+)

Thus, the structure represents a resistance whose value is controlled by a current density of n-metal junction, that is, by nature, similar to the FET, but is controlled by current density. Due to the fact that the intensity of light radiation directly controls the current density, which in turn controls the resistance of the structure, this structure has the internal photoelectric gain.

7. Structures with a heterojunction

Performing a three-barrier photodiode structure based heterojunction allows one to control its spectral respons: take a selective sensitivity or enhance the optical range, in the long or short waves. Increasing energy band gap of the base region can cover the short-wave part of the spectrum, while reducing the energy band gap of p-type region can reduce the sensitivity to shorter wavelengths until the completion of the selective sensitivity is determined by the potential barrier of n-metal. Reducing the potential barrier height of n-metal can expand the optical range to longer wavelengths.

In the case of a three-barrier photodiode Au-n$Al_{0.1}Ga_{0.9}As$-pGaAs-Ag-structure of the current transport mechanism similar to the mechanism of homojunction structure, with the difference that on case of reverse biased n-p-heterojunction with increasing voltage the current dependence is changed from the linear to quadratic, which can be explained by the mechanism of space-charge-limited current transport mechanism. Therefore, in this mode include not observed internal photocurrent gain. However, in a case of forward biased heterojunction the structure has the internal photoelectric gain (Fig. 6.), the magnitude of which increases with both increasing the operating voltage and intensity of light. The dependence of photocurrent on light intensity becomes superlinear character.

Spectral characteristics have also shown that the quantum efficiency in a direct displacement of n-p-heterojunction regardless of the surface to be illuminated in a broad spectral range from 0.95 to 1.3 eV (0.8 to 1.6 microns) unchanged, Fig. 7. By increasing the applied voltage to 65 volts at a radiation power of 0.2 mW/cm^2, the quantum efficiency of the structure increases to 2.77, i. e. there is an internal photoelectric gain.

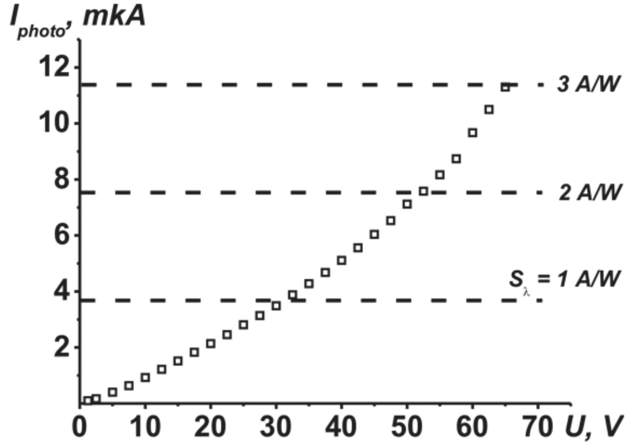


Fig. 6. Photocurrent of the three barrier structure with heterojunction as a function of bias voltage

As noted above, in the structures long base region is depleted of majority carriers and the impurity goes into a neutral state. To verify this situation have been investigated with the basic structure of the area containing deep impurity levels of oxygen. In this case, the compositions heterolayers and metals were chosen so that the height of the barriers have similar values and do not affect the current transport mechanism, and allowed us to determine the influence of deep impurity. In Au-p$Al_{0.05}Ga_{0.9}In_{0.05}As$-nGaAs:O-Ag-structure for both polarities of bias the current-voltage characteristics, spectral response and capacitance-voltage characteristics were identical. Spectral characteristics when excited by heterolayer show that the maximum photocurrent due to excitation of carriers from metal with a characteristic tail of the excitation of carriers from deep levels of oxygen, Fig. 8.

Raising the temperature leads to a broadening of the spectral characteristics of a clear manifestation of the photocurrent in the impurity region of the spectrum caused by oxygen levels (Fig. 9.), and for a given temperature increase of confining the illuminated metal-semiconductor junction bias voltage leads to a simultaneous increase in the photocurrent spectrum in the whole range with simultaneous spectral broadening.

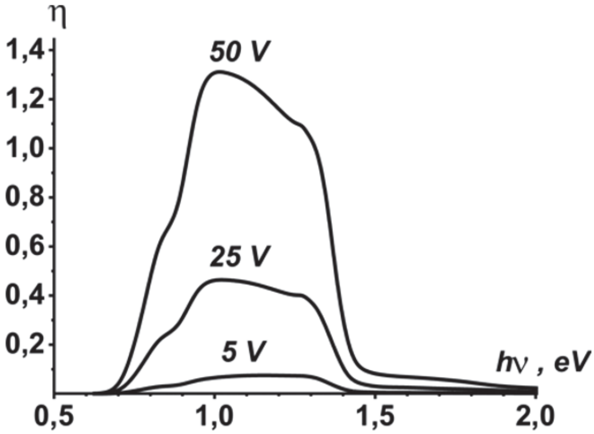


Fig. 7. Spectral response of the three barrier structure with heterojunction at different bias voltages and in bias polarity (+)m-p-n-m(-)

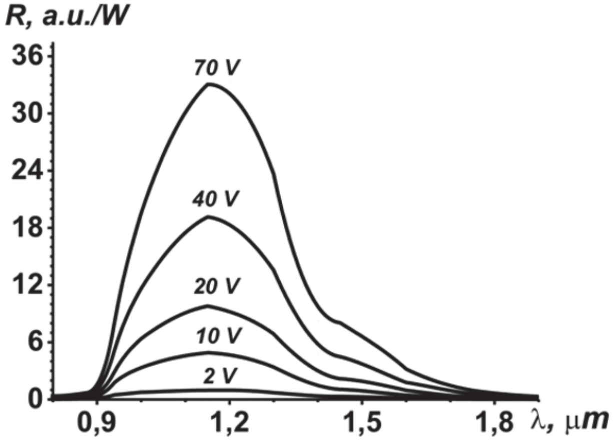


Fig. 8. Normalized spectral response of the three barrier structure with deep impurity levels of oxygen at different bias voltages and in bias polarity (+)m-p-n-m(-)

8. Some perspectives of multibarrier photodiode structures

Multibarrier photodiode structure with an appropriate choice of design parameters may provide a basis to create new structures with improved properties that are of interest for micro and optoelectronics.

Low-capacitance current-controlled transistor can be created can be created by forming a planar rectifying and ohmic contacts to the surface of a thick n-type region of the m_1-p-n-structure. The result will be m_1-p-n-m_2-structure with an ohmic contact to the base n-type region. Capacitance of the structure will be determined by the geometric dimensions of the structure. It creates a voltage forward bias p-n-junction is applied to the electrodes of the potential barriers, and input to the ohmic contact and the contact potential barrier. By analogy with the field-effect transistor contact potential barrier, one might say, carry out the role of the drain and source, an ohmic contact – the role of the gate. However, in contrast to the FET output characteristics are controlled by the current of the gate. In the absence of the input signal through the structure is minimal and determined by the resistance base and lockable metal-semiconductor interface.

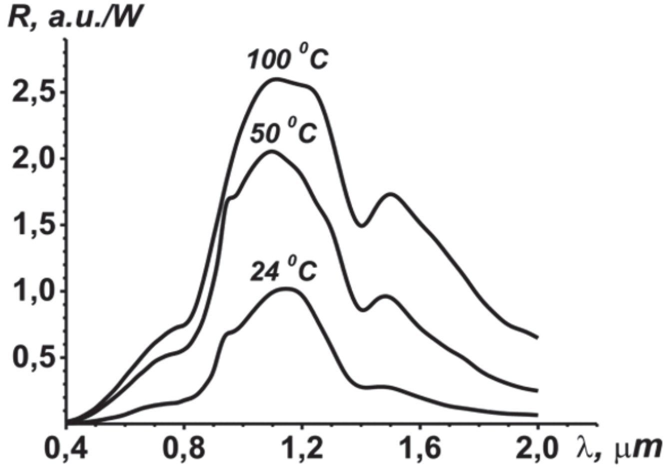


Fig. 9. Normalized spectral response of the three barrier structure with deep impurity levels of oxygen at different temperatures and in bias polarity (+)m-p-n-m(-) at 2 V.

Small change in the gate current, i.e. in the current flowing through the barrier n-m$_2$ leads to a stronger change in the total current through the structure. At the same time the output characteristics are obtained with characteristics similar to the static induction transistor.

In another embodiment, instead of the potential barrier is proposed to form a semiconductor n-p-junction. As a result multibarrier photodiode will be an m$_1$-p-n-p structure with an ohmic contact to n-base. The operating mode will create a voltage applied to the contacts of the barrier and the p-contact area. Useful signal will be fed to the resistance connected to the base and the p-region, or as a signal required for the gain can be a light signal fed to the n-p-junction, where you will create short-circuit current is proportional to the intensity of the radiation. As a result, the output is the amplified signal, ie, the proposed structure will have multibarrier reinforcing properties.

Highly sensitive photodetector can be created by the serial connection m-p-n-structure to p-n-junction. The result is a four barrier m-p-n-p-n-structure including a three-barrier m-p-n-p and bipolar n-p-n-structure. Operating voltage is applied to the external contacts m$_1$ and n-type region with a positive polarity to the contact potential barrier. In the dark current through the structure is determined by the electronic component of the collector p-n-junction, where the electrons have a significant barrier. Under illumination of the collector junction is created that matches the sign of the photocurrent to the dark current and summed. Coefficient of internal photoelectric amplification will consist of works of the gain on the part of a three-barrier transistor gain.

Multibarrier photodiode structures are sensitive to impurity and intrinsic emission can be created by the formation of a nonuniform distribution of deep impurities in a long base n-region in m-p-n-structure. The structure is a thin stripe of p and a thick n-type lightly doped layer (300 microns), which create internal barriers without illumination, did not exceed a few kT. However, if covering own light barrier height can prevail kT, leading to a reduction in current through the structure. When excited by light in the impurity region through the structure will increase.

9. Conclusion

In multibarrier mpnm-photodiode structures with the effect of closure of adjacent oppositely biased junctions, the mechanism of charge transport is determined by the depletion of the major carriers in the base, leading to the development of transitional processes in n-type region with the subsequent transition to a neutral donor state. The degree of depletion n-region and its specific resistance are determined by current density of electrons emerging from semiconductor-metal junction; the dependence of current on voltage obeys a power law with an exponent close to unity and is due by the day the main part of the external voltage on the depleted n-region.

Determining the noise and frequency properties of photodiode structures low capacitance and dark current distinguishes multibarrier structure compared with other types of detectors.

Performing a three-barrier photodiode structure based heterojunction allows you to control its spectral range, a selective sensitivity and enhance the optical range, in the long or short waves. Reducing the height of the barrier metal-semiconductor optical range can be extended to longer wavelengths.

In multibarrier photodiode structures of the internal photoelectric amplification controlled operating voltage and an order of magnitude more sensitive unijunction diode photodiode. For their work does not require any cooling at room temperature provides the required operating modes defined spectral regions (0.9 microns, 1.3 microns, 1.5 microns) with low values of capacitance of the order 0,2-0.5 pF/mm^2. In this case, the dark current for a voltage of 100 V was 40-100 nA. Internal photoelectric amplification of photocurrent is provided from the outset the applied voltage, ie, they possess sufficient sensitivity to record from low supply voltages (5 V). Due to the high input resistance are easily switched with the field-effect transistors and integrated circuits.

Thus, in the above material is presented original experimental data on the principles of creating improved multibarrier photodiode structures, some features of their photoelectric characteristics when exposed to light and heat radiation, the results of the analysis of processes of charge transport and photocurrent gain.

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