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Investigation of the Physical Processes in BISPIN Structures in Pulsation Mode

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Abstract—The mechanisms of the formation of the peak value of the electronic component of the total current through a BISPIN-device in various modes of pulsation are considered. The results of the experimental and theoretical studies of the electronic component of the current through the structure on the supply voltage and load resistance are given. A theoretical model to explain the observed dependence is proposed. A good agreement between the calculated and experimental results is obtained.

Keywords: BISPIN device, current oscillations, sensor of light flux

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A bishifted junction with injection instability (BISPIN) is a functional element of microelectronics wherein the properties of a photodetector and generator are integrated so that it converts the incident light flux into a regular sequence of pulses with a sufficiently large amplitude of the current [1–4]. In this case, the pulse repetition frequency in certain modes is proportional to the light flux and the device can serve as a light flux sensor.

A good start in developing BISPIN devices and their applications in various areas related to the optical radiation photoreception was made. Using the crystals of BISPIN photodetectors one can create optron converters with frequency output having one or more light emitting diodes (LEDs). The sensitivity of such optrons by the input ranges within the range of 1–100 μm, which ensures their management using CMOS circuits. In turn, the output of BISPIN optrons can be easily adjusted to the TTL level. In the BISPIN unit one can identify the fragments of the structure, which play the role of known semiconductor devices, such as the bipolar transistor, field effect transistor with control p–n junction, thyristor, rectifier diode, photodiode, and varactor. Therefore, these structures continue to be studied and the results of these studies are widely used [5].

Figure 1 shows the design of the BISPIN structure [1], the scheme of its commutation, and the shape of the pulses of the current generated in the structure in the mode of pulsations.

As shown in [2], there are three different states of the BISPIN structure: the stationary state with low conductivity; the steady state with relatively high conductivity; and the state in which the current flowing through the structure is oscillating.

Under certain threshold conditions, the closed state of the BISPIN structure becomes unstable and the structure switches to a conducting state like an avalanche. If the device is in the mode of an oscillating

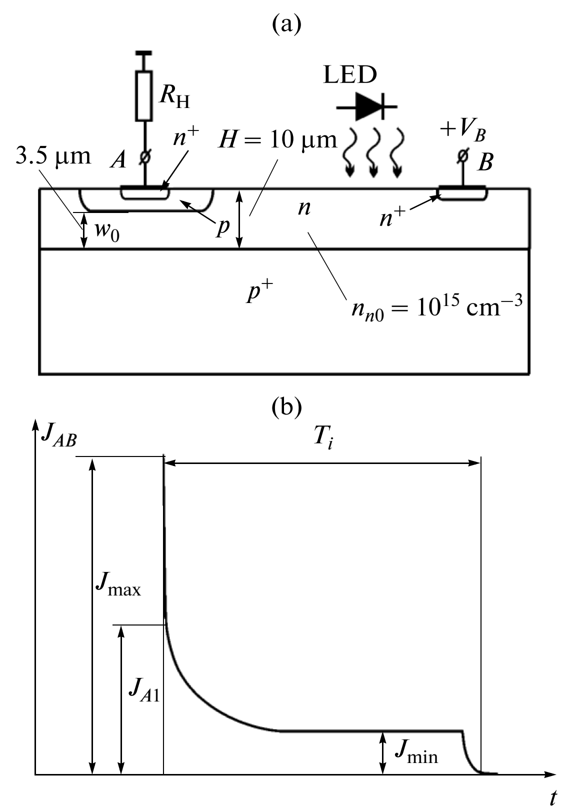

Fig. 1. The design of the BISPIN structure (a) and the shape of current pulses in the pulsation mode (b).

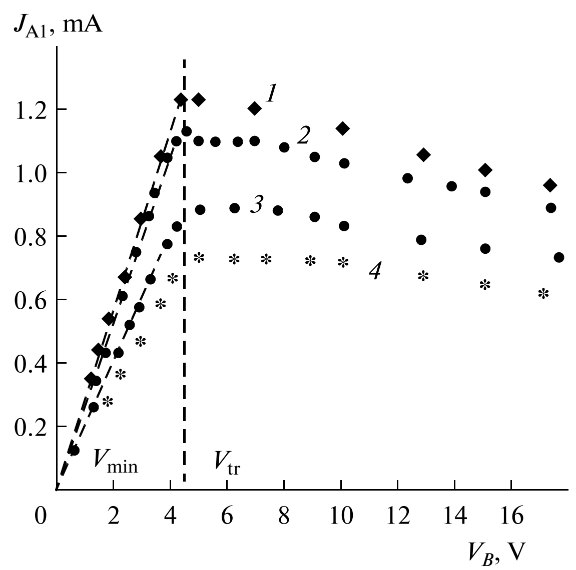

Fig. 2. Dependence of current J_{A1} on supply voltage V_B at various load resistances: *1* — 33 Ohm; *2* — 547 Ohm; *3* — 1540 Ohm; *4* — 2290 Ohm.

current, the open state of the unit becomes unstable, and the BISPIN structure is also closed like an avalanche after a certain time. During the conductive state phase with duration T_i (see Fig. 1) the pulse of current is observed in the load resistance.

The mechanism of positive feedback [3], under the influence of which the structure opens like an avalanche, is slightly different, depending on voltage V_B. Nevertheless, the general shape of the pulses of the current generated remains unchanged. At the moment of switching there is a short splash of the current with amplitude J_{max} and duration of a few nanoseconds. After having switched like an avalanche in the conducting state, the current in this structure abruptly decreases up to the value J_{A1}. Further on, the current decreases slowly and tends to the constant value J_{min}. At the end of the pulse the current decays exponentially to zero. The values J_{max}, J_{A1}, $J_{min,}$ and T_i are the main parameters of the output pulse of the generator based on the BISPIN structure [4]. All of these pulse parameters depend on the illumination, voltage, load resistance, and temperature.

This paper analyzes the formation mechanism of current J_{A1}. In this case, the processes occurring in the structure when forming the magnitude of J_{A1} are developed as follows.

In the absence of light, the floating potential of the substrate is almost equal to the potential of contact *B*. Direct bias is created under the influence of light in the structure of the p^+–n junction (hereinafter, distributed junction). This leads to the injection of holes through the p^+–n-junction from the p^+-substrate to the n-film. In the region where the p-region of the n^+–p–n transistor structure is located above the p^+–n junction, the field of the p–n junction collects the holes and they then fall into the p-base of the transistor, playing the role of the base current. As a result of the transistor gain, the electron current from contact *A* is much higher. Having passed through the active base of the transistor and collector, the current flows along the n-film to contact *B*. The role of the FET transistor with the controlling p–n junction is played by the region of the structure under a passive transistor base. The electron current flowing along the distributed junction causes the reduction of the potential of the nth layer (compared to the potential of contact *B*) when approaching the symmetry axis of the transition structure. The floating potential of the substrate does not depend on the coordinates. A skew offset of the p^+–n junction arises. This causes the redistribution of direct current of holes in favor of the part of the p^+–n junction under the transistor and, correspondingly, the electron current through the transistor increases, etc. An avalanche that increases in current through the structure occurs. Maintaining the positive feedback requires more holes from the substrate to the base of the transistor, i.e., the source of the holes is required. Two processes are the sources of additional holes.

The first process is associated with the redistribution of photoholes coming into the substrate due to the formation of an asymmetric bias of the p^+–n junction, the second (more important) process is associated with recharging the barrier capacitance of this transition.

As a result, at the time of switching, the current through the structure in the plane of the collector junction of the local transistor has two components, the hole and electron components. The hole component flows through the circuit: power supply–contact *B*–its spreading resistance R_s–distributed p^+–n junction–vertical thyristor–load resistor.

The electronic component of the current flows through the circuit: power supply–contact B–spreading resistance of collector of the local transistor–transistor structure–load resistor.

After recharging the barrier capacity through the BISPIN structure, only the electronic component of the current in the cross section of the structure considered will flow, the value of which is determined primarily by the spreading resistance of the collector region of the transistor in the deep saturation mode and the load resistance. This moment of time corresponds to the second highlighted part of the pulse, in which the current decreases from J_{A1} to J_{min}.

The spreading resistance of the collector is mainly determined by the channel properties of the fragment of the structure which is located under the passive base of the transistor. Due to this the dependence of current JA1 on the voltage on contact *B* is expected to be similar to the drain characteristic of FET. However, experimental dependences $J_{A1}(V_B)$, registered at various loading resistances, are dissimilar compared to the usual drain characteristics (Fig. 2). In the voltage range $V_{min} < V_B < V_{over}$, the experimental points nearly lie on a line, whereas the steeper range of the usual characteristics of the channel transistor drain is nonlinear. At $V_B > V_{over}$ the part of the curve with thesaturation current is absent on dependence $J_{A1}(V_B)$. Here, V_{min} is the supply voltage below which the pulsations do not appear under any circumstances, V_{over} is the overlap voltage upon which the regions of the spatial charge of the collector junction of the local transistor and distributed junction are overlapped in the absence of illumination [3].

To explain the dependences obtained it should be noted that the drain current channel fragment of the BISPIN structure depends on the excess charge ΔQ, created by the holes which are released from the substrate at the base of the transistor. For the quantitative calculation of dependence $J_{A1}(V_B)$, the analytical expressions for the family of drain characteristics are required, depending on the charge of the excess holes which came into the region of both bases of the vertical thyristor BISPIN structure. Standard methods for setting the family of the drain FET characteristics to control the p–n junction are not suitable, since in this case the field-effect transistor operates at a forward bias on the gate (both transitions bounding the channel are biased in the forward direction).

Let us express the family of drain characteristics of the saturation current through the transistor whose dependence on the photocurrent flowing from the substrate is shown in Fig. 3.

There is a relation for the normal FET operation (reverse bias on the gate) between saturation current J_{sat} of the drain and saturation voltage V_{sat}:

$$J_{sat} = J_{sat\,max}\left(\frac{V_{sat}}{V_{cut}}\right)^2, \tag{1}$$

where $J_{sat\,max}$ is the maximum saturation current of the transistor drain at a zero bias on the gate; V_{cut} is the cut-off bias of the channel which is equal to the overlap bias V_{over}.

As a first approximation, we assume that in the case of a forward biased gate the character of dependence $J_{sat}(V_{sat})$ is preserved. As $J_{sat\,max}$ in (1) one can take the minimal current of drain $J_{min} = 420$ μA (see Fig. 3) for the stationary open state of the BISPIN structure; as V_{cut} one can take the saturation voltage of the minimum drain characteristic $V_{sat\,min}$, which is $V_{over} = 4.5$ V in the case considered. Given that on the steep branch the drain characteristic $J_{SI}(V_{SI})$ can be reasonably well approximated by a polynomial of the second order degree and using (1) the required analytical expression for a family of drain characteristics can be written as follows:

—on the steeper branch

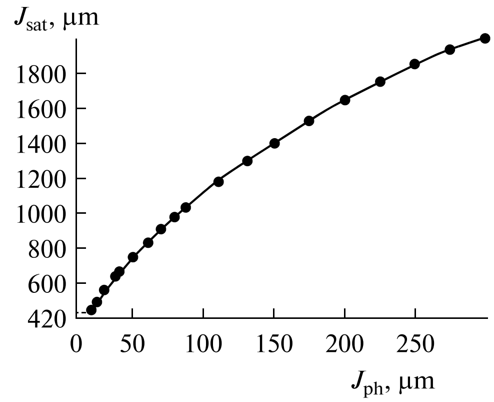

Fig. 3. Dependence of saturation current J_{sat} of the channel fragment of the structure on photocurrent J_{ph}.

$$J_{SI}(V_{SI}) = J_{sat}(\Delta Q) - \frac{J_{min}}{V^2_{sat\,min}}\left\{V_{DE} - V_{sat\,min}\left[\frac{J_{sat}(\Delta Q)}{J_{min}}\right]^{\frac{1}{2}}\right\}^2, \tag{2}$$

—on the gently sloping part

$$J_{DE}(V_{DE}) = J_{sat}(\Delta Q), \tag{3}$$

where $J_{sat}(\Delta Q)$ is the saturation current of the drain depending on the charge of the holes injected from the substrate.

By analogy to (1), the saturation voltage of drain characteristic V_{sat} can be defined as

$$V_{sat} = V_{sat\,min}\left(\frac{J_{sat}}{J_{min}}\right)^{\frac{1}{2}}. \tag{4}$$

If the local bipolar transistor is in the saturation mode, then the main part of the excess carriers is stored in the reservoir under the active base due to the doping ratio of the collector and base regions. The lifetime in this region is unknown, but it should be greater (at least due to the lower doping) than the lifetime in the base of the transistor which is equal to 1.8 μs. By introducing the effective lifetime τ_{eff}, characterizing the process of recombination in both bases of the vertical thyristor structure, one can find a relationship between the total charge ΔQ of the excess holes in these bases and photocurrent J_{ph}. Then, the function $J_{sat}(\Delta Q)$ can be obtained from the dependence $J_{sat}(J_{ph})$ shown in Fig. 3, provided that $\Delta Q = J_{ph}\tau_{eff}$.

In the case considered the experimental dependence $J_{sat}(J_{ph})$ is rather well approximated by a polynomial of the third degree:

$$J_{sat}(J_{ph}) = 172 + 14.81J_{ph} - 0.078J^2_{ph} + 2.41 \times 10^{-4}J^3_{ph}. \tag{5}$$

Here, the currents J_{sat} and J_{ph} are measured in μA. Photocurrent J_{ph} is related to ΔQ by $\frac{\Delta Q}{\tau_{eff}} \times 10^6$, where ΔQ is measured in coulombs and τ_{eff} is measured in seconds.

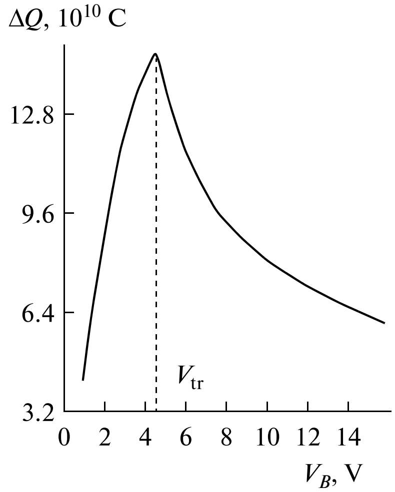

Fig. 4. The calculated dependence of charge ΔQ of excess holes, released at the base of the transistor during the discharge of the distributed capacitance of the transition from supply voltage V_B in the BISPIN structure.

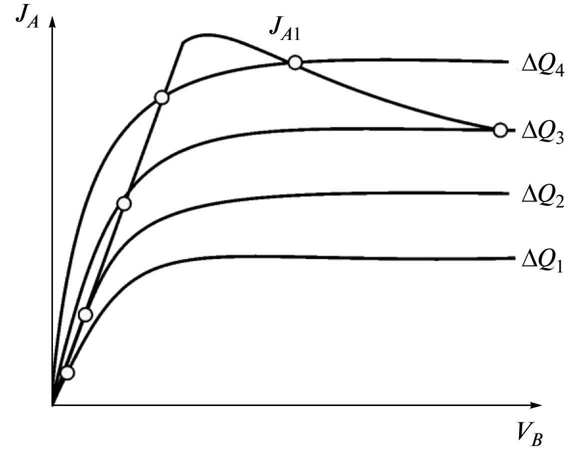

Fig. 5. Scheme of the formation of the dependence of current J_{A1} on supply voltage V_B of the structure (ΔQ is the parameter of a family of drain characteristics of the channel fragment of structure: $\Delta Q_1 < \Delta Q_2 < \Delta Q_3 < \Delta Q_4$).

With an increase of the supply voltage of the BISPIN structure in the mode of pulsations, charge ΔQ injected into the bases of thyristor structure is determined by the discharge of the barrier and diffuse capacitance p^+–n of the junction. However, the calculations show that the charge accumulated on a diffuse capacitance is more than two orders of magnitude less than the charge accumulated on a barrier capacitance. At $V_B < V_{\text{over},}$ charge ΔQ increases with V_B, while at $V_B > V_{\text{over}}$, it decreases with V_B [4]. Figure 4 shows dependence $\Delta Q(V_B)$, calculated in the entire range of the voltage supply variation of the structure. The output performance of the channel fragment of the device corresponds to each charge as a parameter. Therefore, Fig. 5 illustrates qualitatively the dependence of current J_{A1} on the supply voltage. It presents the family of drain characteristics of the corresponding fragment of the BISPIN structure depending on the value of ΔQ. With an increasing supply voltage V_B, the point corresponding to J_{A1} passes from one curve of the family (see Fig. 5) to another. One can see that the obtained dependence $J_{A1}(V_B)$ qualitatively agrees with the experimental curves in Fig. 2. Nevertheless, it is necessary to confirm the proposed model by numerical calculations. The problem is complicated by the fact that in the presence of load resistance the value of ΔQ depends not only on the supply voltage of the BISPIN structure but also on current J_{A1}.

Thus, to determine current J_{A1} and charge ΔQ for fixed values of the supply voltage and load resistance we need to solve the following system of equations:

$$J_{A1} = f(V_{\text{SI}}, \Delta Q),$$
$$V_{\text{SI}} = V_B - J_{A1}R_{\text{load}} - V_{\text{sat.tr}}, \qquad (7)$$
$$\Delta Q = \int_{V_{\text{i}}}^{V_{\text{f}}} C_{\text{B}}(V)dV,$$

where V_{DE} is the drain-emitter bias corresponding to the BISPIN structure fragment playing the role of FET; $V_{\text{sat.tr}}$ is the saturation voltage of the bipolar transistor; C_{B} is the barrier capacitance of the p^+–n junction; $f(V_{\text{DE}}, \Delta Q)$ is the family of drain characteristics of the channel transistor described by (2)–(4). The value of ΔQ in (7) depends on the voltage drop on the barrier capacitance of the main part of the distributed p^+–n junction (V_{f} and V_{i}). The final voltage V_{f} does not depend on the pulsation mode but depends on current J_{A1}. The initial voltage V_{i} on the main part of the distributed p^+–n junction depends on the pulsation regime. In a first approximation, in the valve mode [3], initial voltage V_{i} is equal to the overlap voltage V_{over}. In the photodiode mode, V_{i} is defined by

$$V_{\text{i}} = V_B - V_{\text{over}}. \qquad (8)$$

Therefore, system equations (7) are transformed depending on the voltage supply range of the BISPIN structure V_B, and the position of the working point on the drain characteristic. In total, only two options of these relations are possible for calculating dependences $J_{A1}(V_B)$ and $\Delta Q(V_B)$.

At $V_B < V_{\text{over}}$ and $V_{\text{DE}} < V_{\text{sat}}$, system (7) takes the form of four equations with four unknowns (J_{A1}, ΔQ, J_{sat}, V_{DE}):

$$J_{A1} = J_{\text{sat}} - \frac{J_{\min}}{V_{\min}^2}\left[V_{\text{DE}} - V_{\text{sat}\,\min}\left(\frac{J_{\text{sat}}}{J_{\min}}\right)^{1/2}\right]^2,$$

$$J_{\text{sat}} \approx 14.81\frac{\Delta Q}{\tau_{\text{eff}}}\times 10^6 - 0.78\left(\frac{\Delta Q}{\tau_{\text{eff}}}\times 10^6\right)^2 + 2.41\times 10^{-4}\left(\frac{\Delta Q}{\tau_{\text{eff}}}\times 10^6\right)^3,$$

$$V_{\text{DE}} = V_B - J_{A1}R_{\text{load}} - V_{\text{sat.tr}},$$

$$\Delta Q = \int\limits_{V_{\text{over}}}^{V_B - J_{A1}R_{\text{load}} - V_{\text{sat.tr}}} C_{\text{B}}(V)dV.$$

At $V_B > V_{\text{over}}$ and $V_{\text{DE}} < V_{\text{sat}}$ system (7) takes the form

$$J_{A1} = J_{\text{sat}} - \frac{J_{\min}}{V_{\text{sat min}}^2}\left[V_{\text{DE}} - V_{\text{sat min}}\left(\frac{J_{\text{sat}}}{J_{\min}}\right)^{\frac{1}{2}}\right]^2,$$

$$J_{\text{sat}} \approx 14.81\frac{\Delta Q}{\tau_{\text{eff}}}\times 10^6 - 0.78\left(\frac{\Delta Q}{\tau_{\text{eff}}}\times 10^6\right)^2 + 2.41\times 10^{-4}\left(\frac{\Delta Q}{\tau_{\text{eff}}}\times 10^6\right)^3,$$

$$V_{\text{DE}} = V_B - J_{A1}R_{\text{load}} - V_{\text{sat.tr}},$$

$$\Delta Q = \int\limits_{V_B - V_{\text{over}}}^{V_B - J_{A1}R_{\text{load}} - V_{\text{sat.tr}}} C_{\text{B}}(V)dV.$$

At $V_B > V_{\text{over}}$ and $V_{\text{DE}} > V_{\text{C}}$, system (7) takes the form of three equations with three unknowns (J_{A1}, ΔQ, V_{DE}):

$$J_{\text{sat}} \approx 14.81\frac{\Delta Q}{\tau_{\text{eff}}}\times 10^6 - 0.78\left(\frac{\Delta Q}{\tau_{\text{eff}}}\times 10^6\right)^2 + 2.41\times 10^{-4}\left(\frac{\Delta Q}{\tau_{\text{eff}}}\times 10^6\right)^3,$$

$$V_{\text{DE}} = V_B - J_{A1}R_{\text{load}} - V_{\text{sat.tr}},$$

$$\Delta Q = \int\limits_{V_B - V_{\text{load}}}^{V_B - J_{A1}R_{\text{load}} - V_{\text{sat.tr}}} C_{\text{B}}(V)dV.$$

Numerical solution of system (7) in the entire range of the considered voltages of the BISPIN structure has allowed us to obtain the calculated dependences $J_{A1}(V_B)$. One fitting parameter τ_{eff} was used in the calculations. The best agreement between the theory and experiment was obtained when $\tau_{\text{eff}} = 8$ μs. This value of the effective lifetime is quite realistic. Figure 6 shows the calculated and experimental dependences $J_{A1}(V_B)$ obtained at loading resistance R_{load} of 33 and 2290 Ohm.

For R = 33 Ohm, the coincidence between the calculations and the experiment can be regarded as very good (within the admissible experimental error limit of 5%). For R_{load} = 2290 Ohm, the experimental points lie slightly lower than the calculated ones (the discrepancy with the model reaches 12% at a high supply voltage). This can be explained by the occurrence of a systematic error in the measurement of current J_{A1}; it increases with load resistance and leads to an underestimate of the current.

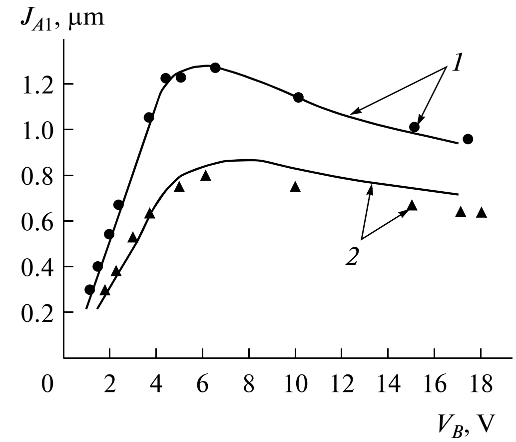

Fig. 6. Experimental (points) and the calculated (solid lines) dependences of current J_{A1} on supply voltage V_B of the BISPIN structure for two values of load resistance: (*1*) R_{load} = 33 Ohm; (*2*) R_{load} = 2290 Ohm.

Thus, we can conclude that the proposed model of dependence $J_{A1}(V_B)$ ensures a good description of the observed and experimental results.

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