New-type silicon bipolar-pixel detector with internal amplification

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***Abstract*. New-type silicon detector of charged particles and photons with internal amplification is considered. Bipolar n^+pn^--transistor pixel placed on a high-purity n^--type silicon substrate is the functional element of the detector. The range being sensitive to ionization is a low-doped ($N \sim 10^{12}$ cm^{-3}) n^- region of the collector with a thickness virtually coinciding with the substrate thickness. A thin base containing one or more n^+ emitters is formed on the surface. The current-amplification gain factor of the emitterbase junction is about 30. Detector prototypes are manufactured in the form of transistor matrices of 3×3 mm^2 and 6×6 mm^2 dimensions with a interpixel spacing of 50 and 100 microns. Results of testing of matrices are presented. The work is supported by the International Science and Technology Center, Project # 3024**

***Keywords*: Silicon bipolar detector**

I. Introduction

For fast detection of coordinate of particles, a detector is to be constructed, which is able to provide the linear amplification of weak signals generated by particle in the detector material just inside the chip. Three ways of internal amplification inside the modern silicon coordinate detectors are mainly used, namely, the use of avalanche multiplication effect in *p-i-n* diodes, one-chip integration of *p-i-n* diode with the preamplifiers input stage inside the pixel, and the use of MOS depletion-channel unipolar transistors (DEPMOSFET). Avalanche photodiodes (APD) are applied as solid-state photo multiplier. The signal amplification is provided by avalanche multiplication of charge carriers in the strong field of *p-n* junction. The disadvantage of such diodes is a poor signal-to-noise ratio caused by the amplification of both the current produced by generated charge carriers and the volume component of the diodes reverse current. A high signal-to-noise ratio takes place only in diodes with reverse current caused by the surface component of the leakage current. Another significant disadvantage of APD is that its structure is under a high back bias, while the operating point is at the prebreakdown range. As the soft avalanche breakdown is provided by the existence of microplasma in different points of $p - n$ junction, than each specific device must be first calibrated by voltage and gain factor. Design peculiarities and matching of appropriate voltage for each APD require an individual approach [1]. As a result, it is very difficult to realize a two-dimensional coordinate-detector matrix using APDs. In the second and third cases the pixel of detector matrix present a structure consisting of *p-i-n* diode and MOS unipolar transistors with *p-n* junction [2] or MOS-transistor [3] amplifying the primary ionization current from *p-i-n* diode. Such a matrix design suppresses significantly the spurious capacitance between the detector and preamplifier and provides sufficiently fast and high amplification of the primary signal that makes it possible to enlarge the signal-to-noise ratio as well. A disadvantage of such detectors is a rather low operating speed, complexity of technological realization and, as a result, a high cost.

II. Functionally integrated bipolar-pixel coordinate detectors of particles

In this work bipolar-pixel coordinate semiconductor detectors are proposed which apply functionally integrated pixel structures [4], [5]. A primary ionization current produced in the pixels *p-i-n* diode by a charged particle is amplified by the transistor structure by 2050 times and immediately inputs into bus-lines connected with emitters of pixels *n-p-n* transistors. Depending on metallization bussing, single pixels placed on 10×10-mm^2 chip can be joined into strips or can form a matrix which makes it possible to detect particles in two-coordinate system. Such a detector can give information on two coordinates, time and energy losses of single particle. The coordinate resolution is determined by the distance between pixels. In our samples it varies from 25 to 100 mm. Standard technological processes are applied during its manufacturing. To design the detector, 100-mm one-side-polish high-resistance n^- silicon wafers with specific resistance $\rho > 5$ kOhm·cm, life time $\tau = 2500\,\mu$s, and orientation $\langle 111 \rangle$ were used. During the elaboration of the detector, a large number of various up-diffusion and annealing regimes, combination of topological elements and so on were tested. In this paper two samples are considered. Two-stage up-diffusion was first carried in a nitrogen (N_2) atmosphere at $900°$C and, second, in a damp oxygen (O_2) atmosphere at $850°$C.

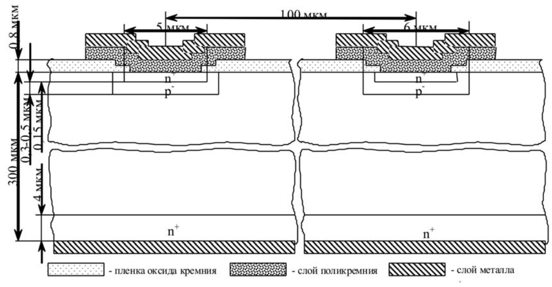

Fig. 1: Structure 1.

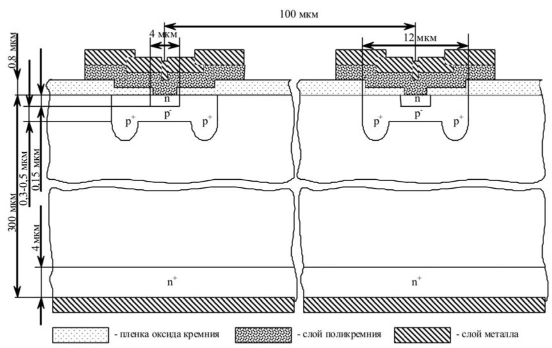

Fig. 2: Structure 2.

As a result, a silicon dioxide layer ~ 0.3 micron thick has been formed. While samples with p^+-guard rings were manufactured, the direct substrate implantation of 100200-keV boron with a dose of 60200 microcoulombs (μQ) was carried out. At all the stages of formation of active regions, ion implantation was applied. To form shallow-lying emitter, arsenic (As) with an energy of 100 keV and dose of 300 μQ was implanted into polysilicon (Si*). Post implantation annealing was carried out at $900°$C in a nitrogen (N_2) atmosphere. The p^+ base region was formed by implanting boron (B) with an energy of 100 keV and dose of 310 μQ through the layer of silicon dioxide (SiO_2) ~ 0.3 micron thick. 100-keV phosphorus with a dose of 300 μQ was implanted and for the gettering into the wafers back side and the annealing was performed at $900°$C during 30 minutes. As a result, several types of different types of pixel structures have been manufactured differing in topological sizes and construction. In this paper two samples are considered which are below named Structure 1 and Structure 2.

Structure 1 (Fig. 1) consists of bipolar transistor floating-base *n-p-n* structures. Interpixel distance take on values 25, 50, and 100 microns in different versions. Depth of 5-mm-diameter emitter occurrence is $0.15 - 0.20$ mm, the depth of 8-mm-diameter base is ~ 0.4 mm after up-diffusion. Polysilicon Si* layer 0.4-mm thick and metal contact are formed over the emitter on the wafer surface. So, the total thickness of the dead layer over the emitter is ~ 1.4 micron. The silicon dioxide thickness in the region between transistors is taken 0.8 mm, thus the total thickness of the layer in this region (where the absorption of particles carries out with no production of electron-hole pairs, which could be collected by electric field) is 0.8-1.4 mm. Structure 2 (Fig. 2) is similar to Struct. 1 as a whole, however it is supplemented with p^+-guard ring so that the total size of base and guard ring is 20×20 mm^2. Let us note that pixels in the structures described in this work are connected in series only, i.e., form some chains but not matrices in the full sense of the word. Fig. 3 demonstrates a real view of one of detector samples. The visible differences of different parts is related to their topological peculiarities.

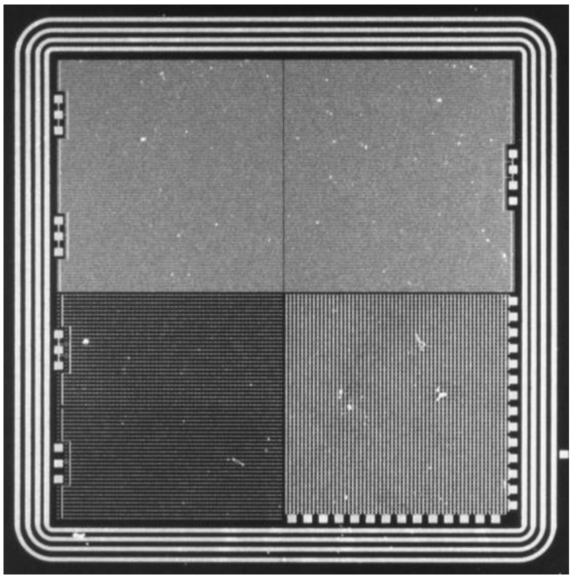

Fig. 3: Sample of topology of pixel detector

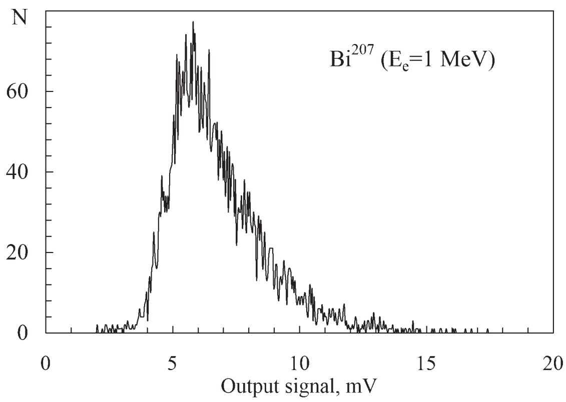

Fig. 4: Amplitude spectrum of structure-output signals produced by relativistic electrons ($E_e = 1$ MeV) emitted by a Bi^{207} source. The distribution asymmetry shows the Landau law behaviour of losses.

III. Static features of pixel detectors

Testing of structures in static regime includes the following parameters: breakdown voltage $U_{\rm break}$, dark current $I_{\rm dark}$, noise voltage $U_{\rm noise}$ at operating bias voltage $U_{\rm bias}$. As these structures prove to be

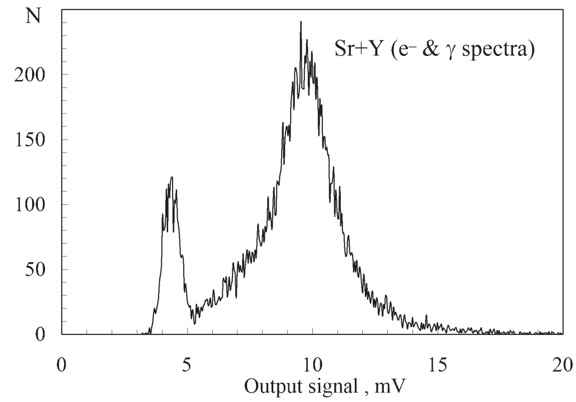

Fig. 5: Amplitude spectrum of output signals produced by electrons and γ-rays emitted by a strontium/yttrium (Sr+Y) source.

photosensitive, all the measurements were carried out in the dark. However, to estimate the influence of ingress of light, all the parameters were also measured under a background illumination. Structure 1 demonstrates $\mathrm{U_{break}} = 200$ V, $\mathrm{I_{dark}} = 500$ nA. Under these conditions, the self-noise amplitude is $\mathrm{U_{sn}} = 1$ mV. Let us note that the noise amplitude increases drastically under background illumination, namely, it becomes as large as $\mathrm{U_{sn}} = 15$ mV at $\mathrm{U_{bias}} = 6$ V. Structure 2 demonstrates $\mathrm{U_{break}} = 100$ V, $\mathrm{I_{dark}} = 150$ nA at $\mathrm{U_{bias}} = 50$. At the same $\mathrm{U_{bias}}$, the noise amplitude is $\mathrm{U_{sn}} = 1$ mV. However, under a background illumination the breakdown voltage $\mathrm{U_{break}}$ decreases down to 9.5 V and the noise amplitude increases up to $\mathrm{U_{sn}} \approx 5$ mV (at $\mathrm{U_{bias}} = 6$ V).

IV. Spectral features of detectors

Fig. 4 demonstrates an amplitude spectrum of structure-output signals produced by relativistic electrons with an energy $E_e = 1$ MeV emitted by Bi^{207} source. An amplifier is used with threshold frequency $f_{\mathrm{thr}} = 1.5$ GHz and input capacitance of ~ 10 pF. The impulses leading edge time at 99% level after the amplifier is ~ 10 ns. The pixel gain is estimated as follows. While taking into account parameters of silicon wafers, space charge volume and so on, we can estimate the total value of charge produced by one relativistic electron inside the structure as $\mathrm{Q_{in}} \approx 2 \cdot 10^4\,\mathrm{pairs} \times 1.6 \cdot 10^{-19}\,\mathrm{Q} \approx 3.2 \cdot 10^{-15}$ Q. While taking into account amplifier parameters, for the distribution maximum we have $\mathrm{Q_{out}} = \mathrm{C} \times \mathrm{U} \approx 12 \cdot 10^{-12}\,\mathrm{F} \times 6 \cdot 10^{-3}\,\mathrm{V} \approx 70 \cdot 10^{-15}$ Q. If so, the gain is $\beta \approx 70 \cdot 10^{-15}/3.2 \cdot 10^{-15} \approx 20 - 25$. The distribution form is asymmetric in accordance with the Landau distribution of small losses in thin layers. Fig. 5 demonstrates an amplitude spectrum of output signals produced by electrons and γ-rays emitted by strontium/yttrium (Sr+Y) source. The gain is specially enlarged by ~ 1.7 times as compared with Fig. 4 to determine the experimental noise level. The distribution form demonstrates an deviation from the Landau distribution caused by a non-monoenergetic nature of electron emission.

V. Conclusion

It is shown that functionally integrated structures can be applied to design pixels of coordinate detector. Integration of *p-i-n* diode and bipolar transistor containing a thin low-doped base makes it possible to design semiconductor detectors of particles with an internal gain of several tens by manufacturing structures with inter-emitter distances less than 100 microns. The structure gain is determined by the operating voltage and construction parameters, namely, by thickness of low-doped base region and emitter. While enlarging the operation voltage from 20 to 70 V, the width of the space charge volume increases from 30 to 300 microns. The signal-to-noise ratio is determined by a number of structure construction peculiarities including, for instance, a large ($\sim$ 1 mm) thickness of metallization layers on the input window area, noises of back-side ohmic contact, large contribution of the generated current in the space charge volume of collector *p-n* junction as well as electronic-section noises. The spectral resolution of bipolar coordinate detector approximately corresponds to that of microstrip detector, however the former has such advantages as a higher processing speed and availability of two-coordinate measurements. Such detectors could be applied in different-field devices related to detection of charged particles, X-rays, light photons and so on.

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