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Short Communication

Equivalent Circuit of Betavoltaic Structure on Silicon pn Diode

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The equivalent circuit of betavoltaics silicon pn diode is proposed. The circuit includes the current source from betavoltaics effect, ideal pn diode, shunt and series resistances, and also barrier capacity with charge on it. The model allows to explain that increasing of charge on the surface silicon *pn* diode must decrease the effectiveness of energy conversion. As example, we showed that the open circuit voltage is decreased during irradiation time from beta source Ni-63 and it rapidly becomes higher after discharging.

Keywords: Charge carriers, Betavoltaic structure, Silicon diode, Equivalent circuit, Betavoltaics effect.

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1. INTRODUCTION

The miniaturization of semiconductor circuits and the development of microelectromechanical systems has led to a decrease in energy consumption. At present, the most economical commercial semiconductor microcircuits consume about 1-10 nanoamperes in the standby mode [1]. In this context, it is of much interest to develop sources of electrical energy based on β isotopes with a long service life. From the practical point of view, the nickel-63 isotope seems to be the most interesting among β-radiation sources.

The activity of nickel-63 amounts to 1-40 mCi/cm^2; however, the most widely used are sources with an activity of 10 mCi/cm^2, by integrating the energy spectrum of which one can obtain a emission power on the order of 1 μW. At present, the efficiency of the transformation of β-decay energy into electrical power is fairly low and does not exceed 0.3% [1-4]. The low efficiency is related to several causes: inelastic scattering of β particles, absorption of β particles in layers where there is no generation of electron–hole pairs, recombination of charge carriers, and so on [5, 6].

In fact, the number of electron–hole pairs generated by one β particle with the energy E amounts to E/E_i, where E_i is the characteristic energy, which is equal to 3.8 eV for silicon. On average, the number of such pairs generated by one β nickel-63 particle amounts to 4500-5000. Under the condition that all generated electron–hole pairs are divided by the field of the *p-n* junction and contribute to the current, while the electromotive-force voltage amounts to about 0.35 V, one can find that the theoretical limit for the efficiency of silicon structures is no greater than 10-15%.

Many authors showed that short circuit current and open circuit voltage increase nonlinear with the activity of nickel-63 [5-8]. Unfortunately, they didn't explain this effect and just only are limited by description of experimental data. In this work, we proposed the equivalent circuit of betavoltaic structure on silicon pn diode which includes the charge effect of surface and allows to explain the experimental data of decreasing effectiveness of energy conversion.

2. EQUIVALENT CIRCUIT OF BETAVOLTAIC STRUCTURE

Usually for description of betavoltaic structure they use the electrically equivalent for solar cell, which includes current source, the ideal diode, shunt R_{Sh} and series R_S resistors and load resistor R_L. In the case presence of negative charge from beta- particle source we must to take in the consideration the influence of barrier capacity C_b of pn diode which is connected in parallel to the ideal diode (Fig. 1). If we have irradiation from resource of beta- particles then the negative charge $-Q_S$ is accumulated on the surface of *pn* diode. Of course, this charge will be compensated by generation current I_{PV}, what's why the voltage-current characteristic will be moved to the left on the bias $U_b = -Q_S/C_b$. It's known that C_b depends on applied potential to the diode, so U_b also depends on the potential and bias the voltage-current characteristic will be not linear.

According to the equivalent circuit of betavoltaic structure we can write the equation for circuit I and voltage U (Fig. 1):

$$I = I_{PV} - I_D - I_{Sh} \tag{1}$$

$$U_{Sh} = U + I \cdot R_S - {}^{Q_S}/_{C_b} \tag{2}$$

$$I_{Sh} = {}^{U_{Sh}}/_{R_{Sh}} \tag{3}$$

$$I_D = I_0 \left[e^{\frac{U_{Sh}}{n \cdot U_T}} - 1 \right] \tag{4}$$

where I_D is the diode current and I_{Sh} is current throw the shunt resistor, U_{Sh} is the voltage on the shunt resistor, n is the linearity factor, U_T is the temperature potential.

This equivalent circuit scheme allows us to

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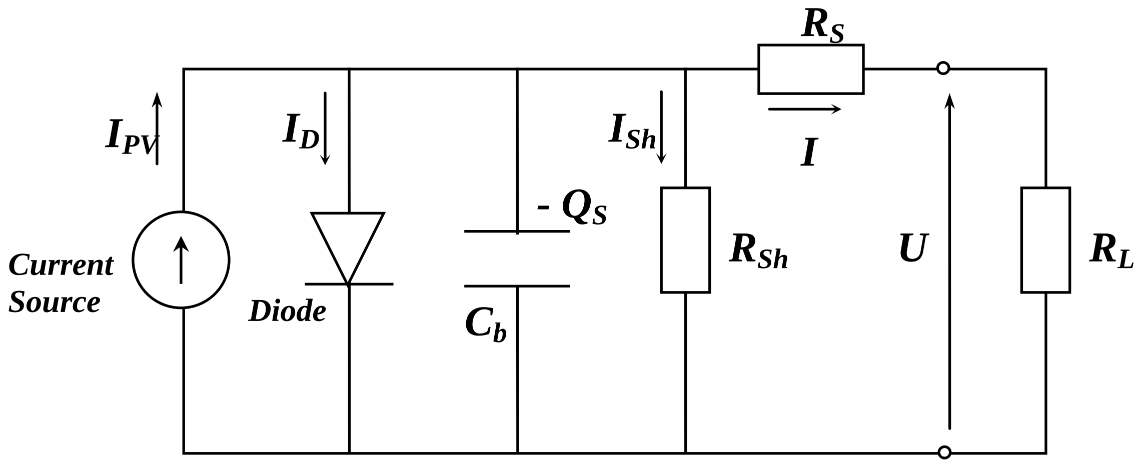

Fig. 1 – Equivalent circuit of the betavoltaic structure on the silicon pn diode: current source based on betavoltaic effect with generation current I_{PV}, the ideal diode with current I_D, barrier capacity C_b with charge – Q_S, shunt resistor R_{Sh} with current I_{Sh}, series resistor R_S with current I, load resistor R_L with voltage U

understand how the current-voltage characteristics is changed under the charge during beta- particles irradiation.

3. EXPERIMENTAL DATA ON OPEN CIRCUIT VOLTAGE

Solid-state beta sources with an activity of 10-40 mCi were used in the work. The samples were pin diodes made using homoepitaxial growth of silicon on silicon with simultaneous doping with phosphorus to a level of 10^{17}-10^{18} cm^{-3} and a *p-n* junction depth of 1.6-1.8 μm. In this case, p-type silicon with a doping level of 7.2×10^{12} cm^{-3} was used as the substrate. To measure the dynamics of charge accumulation, the sample surface was treated with hydrofluoric acid for 30 seconds to introduce a large number of defects to the surface. As shown by measurements, the generation current varied non-linearly from 40 to 80 nA with an increase in the activity of the beta source from 10 to 40 mCi. The open circuit voltage (U_{oc}) does not reach the nominal value, for this type of sample is equal to 0.35 V, but is limited to voltages at which the generation current becomes equal to the leakage current [1].

The most interesting results were obtained by studying the effect of a prolonged exposure to beta-radiation with an activity of 20 mCi on the generation of current and U_{oc}. The generation current was 40-50 nA and did not degrade for more than a year. The dependence of the U_{oc} voltage on the irradiation time is shown in Fig. 2, the maximum value of the voltage was 18.5 mV. The voltage decreases more than three times in the first 15 days, then experiences jumps in the range of 6-15 mV. At different time intervals, a linear decrease to a value of 6-7 mV occurs first, then an output to a constant value and under certain conditions a sharp jump [1].

It is interesting that the angle of inclination of the time dependences of the voltage is the same at different time intervals (Fig. 2). Taking into account that the intensity of radiation of nickel-63 negatively charged beta particles is about 10 μC per day, this effect can be associated with charging the sample surface. The main part of the beta particles penetrates into the interior of the sample, generates a current in the space charge region, and then the accumulated negative charge flows through the p-n junction pins. A small part of the beta particles falls into the traps at the oxide-silicon interface and creates a surface charge, which changes the observed value of the voltage. A numerical estimate of the accumulated charge at the boundary during the first ten days gives values of the order of 10^{-10} C, which is approximately $1/10^5$ of all the beta particles that have fallen on the sample during this time.

At the time points indicated by the arrows (Fig. 2), the solid-state beta source was mechanically moved along the sample area, which provided the conditions for discharge. In the future, the dynamics of charge accumulation was random, but the value of the voltage in the peaks reached 10-17 mV, which indicates that there was no degradation of the structure under the action of beta radiation.

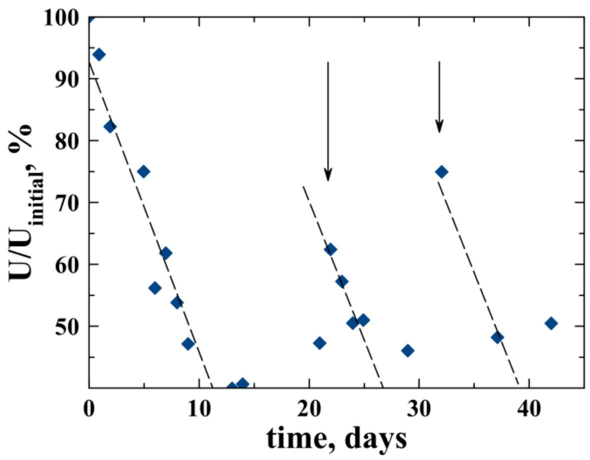

Fig. 2 – Dynamics of the changing of normalized open circuit voltage during irradiation time from beta source Ni-63 with activity of 40 mCi/cm^2. Dashed lines show the charge speed of surface of the silicon pn diode. Arrows show the time moments when the discharging was occurred by moving the Ni-63 plate on the surface of silicon *pn* diode

So using equivalent circuit we can calculate the U_{oc}, which is a good quality agreement with experiment:

$$U_{oc} \approx n \cdot U_T \cdot ln\left[\frac{I_{PV}}{I_0} + 1\right] - {Q_S}/{C_b}. \qquad (5)$$

4. CONCLUSION

Thus the equivalent circuit scheme is proposed for description of betavoltaic effect on the silicon pn diode. The model includes the current source, the ideal diode, shunt and series resistors and load resistor and also barrier capacity with negative charge. According with this scheme the current characteristics will be moved to the left on the bias depends on the barrier capacity and charge. Experimental measurements of dynamics of the changing of open circuit voltage during irradiation time from beta source Ni-63 can be explained from proposed model.

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