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Abstract

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STUDY OF A p–n JUNCTION IN SILICON BY MEANS OF LIQUID ELECTROPHOTOGRAPHIC DEVELOPERS

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It is known that if a voltage is applied to a semiconductor p–n junction in the blocking direction, a space-charge region appears in the junction. Assuming that all impurities are completely ionized, we obtain the density of this charge

$$\rho = e(N_\mathrm{d} - N_\mathrm{a} + p - n), \tag{1}$$

where $N_\mathrm{d}, N_\mathrm{a}, p$, and n are, respectively, the densities of donors, acceptors, holes, and electrons, and e is the electron charge.

Usually in (1) the contribution of free carriers ([1]) is neglected and the case of a completely depleted p–n junction is considered. Then the space-charge region has sharp boundaries x_n and x_p (Fig. 1), and for the potential drop in the junction one obtains the expression

$$-U - U_\mathrm{k} = \frac{4\pi e}{\varepsilon} \int_{x_n}^{x_p} xN(x)\, dx, \tag{2}$$

where $N(x) = N_\mathrm{d} - N_\mathrm{a}$; U is the applied voltage; U_k is the contact potential difference in the p–n junction; ε is the dielectric constant.

Fig. 1. Distribution of the impurity concentration $N(x) = N_\mathrm{d} - N_\mathrm{a}$ in the region of a p–n junction

The model of a completely depleted p–n junction, as shown in works ([2,3]), gives good results for germanium and especially for silicon. Differentiating (2), taking x_n and x_p as parameters, we obtain

$$dU = -\frac{4\pi e}{\varepsilon} N(x_p) x_p\, dx_p + \frac{4\pi e}{\varepsilon} N(x_n) x_n\, dx_n. \tag{3}$$

Since the p–n junction as a whole is neutral, the equality holds

Figure 2

Figure 1: Figure 2

Figure 3

Figure 2: Figure 3

$$\int_0^{x_n} N(x)\,dx = \int_0^{x_p} N(x)\,dx. \tag{4}$$

From (3) and (4) we obtain the expressions

$$|N(x_n)| = \left|\frac{dU}{dx_n}\right| \frac{\varepsilon}{4\pi e\,|x_p - x_n|}; \tag{5}$$

$$|N(x_p)| = \left|\frac{dU}{dx_p}\right| \frac{\varepsilon}{4\pi e\,|x_p - x_n|}. \tag{6}$$

From (5) and (6) one can determine the impurity concentration $N(x)$ in the region of a p–n junction if it is known how they vary with the applied vol-

To the article by A. S. Litonov and L. G. Yuzekselieva, p. 1260

Fig. 2. Pattern of a p—n junction in silicon, developed with a liquid electrophotographic developer.

Fig. 3. Pattern of the region of negative space charge, developed with a liquid electrophotographic developer at voltages: a—1.3 V, b—50 V, and c—80 V.

To the article by L. V. Kirenskii and V. G. Pyn' ko, p. 1267

Fig. 1. Electron diffraction pattern of a cobalt film deposited in vacuum at 10^{-4} mm Hg on a NaCl crystal heated to 200°.

Fig. 3. Electron-microscopic image of the domain structure of a cobalt film grown on NaCl. The structure arose as a result of demagnetization of the film in an alternating field. 1100×.

by comparing the thicknesses of the regions of positive and negative space charges, x_n and x_p.

Figure 1

Figure 3: Figure 1

Figure 3

Figure 4: Figure 3

Fig. 4. Dependence of the reverse voltage applied to a p–n junction on the square of the thickness of the space-charge region. The numbers at the curves correspond to the sample numbers in Table 1.

Figure 5: Fig. 4. Dependence of the reverse voltage applied to a p–n junction on the square of the thickness of the space-charge region. The numbers at the curves correspond to the sample numbers in Table 1.

Owing to the presence of space charge in the p–n junction, it becomes possible to reveal the junction and to study it with the aid of liquid electrophotographic developers.

We studied p–n junctions in p-type silicon obtained by lithium diffusion. The boundary of the p–n junction was revealed as follows. A voltage of ~ 80 V was applied to the junction in the blocking direction. A liquid electrophotographic developer[4] was applied as a drop to a well-polished surface (perpendicular to the surface of the p–n junction). To increase the sharpness of development, an additional electrode[4] was used. The developer particles, carrying a positive charge, were deposited on the p-region of the junction (Fig. 2). It was found that the accuracy in developing the junction boundary depends only on the accuracy of polishing. The error in the experiments performed was less than $10\,\mu$.

Fig. 4. Dependence of the reverse voltage applied to a p–n junction on the square of the thickness of the space-charge region. The numbers at the curves correspond to the sample numbers in Table 1.

In order to develop the region of negative space charge, conditions were created for the developer particles to settle only on this region. The results are shown in Fig. 3 for three applied voltages.

Since for the n-region of the investigated p–n junction the relation $N_{\mathrm{D}} \gg N_a$ is satisfied, the thickness of the region of negative volume charge turns out to be much greater than the thickness of the region of positive charge, and then $x_p - x_n = \delta \approx x_p$. In this case equality (5) is transformed into the following:

$$\left|N(x_p)\right| = \frac{\varepsilon}{2\pi e}\left|\frac{dU}{d(\delta^2)}\right|. \tag{7}$$

The dependence $U(\delta^2)$, obtained experimentally with the aid of a liquid electrophotographic developer and shown in Fig. 4 for four samples, turns out to be linear. This fact is not difficult to explain, because in our case the donor concentration in the p-region of the junction falls very steeply to zero and $|N(x_p)| = |N_D - N_a| \approx N_a$, and from (7) it follows that $dU/d(\delta^2) = \text{const}$.

Table 1

Acceptor concentration N_a in p-type silicon

Sample No.	$N_a \cdot 10^{-13}$, cm^{-3}: by specific resistance	$N_a \cdot 10^{-13}$, cm^{-3}: by capacitance measurement(5)	$N_a \cdot 10^{-13}$, cm^{-3}: by electrophotography of the p-n junction	Sample No.	$N_a \cdot 10^{-13}$, cm^{-3}: by specific resistance	$N_a \cdot 10^{-13}$, cm^{-3}: by capacitance measurement(5)	$N_a \cdot 10^{-13}$, cm^{-3}: by electrophotography of the p-n junction
1	1.77	–	1.06	8	4.23	3.47	1.42
2	1.86	1.77	3.21	9	4.83	5.79	4.01
3	1.94	1.84	0.69	11	6.32	–	14.6
4	2.33	2.19	1.1	12	7.15	–	3.22

From the slope of the straight lines in Fig. 4, using (7), the acceptor concentration N_a in silicon was determined. The results are given in Table 1 for

8 samples. In the first and second columns of the table, for comparison, the acceptor concentrations calculated from the specific resistance of silicon (under the assumption that all acceptor impurities are completely ionized) and from measurement of the capacitance of the p–n junction ([5]) are given. As can be seen from the table, the three methods give close results. This fact confirms the objectivity of the proposed method. In addition, the method of electrophotography of the p–n junction possesses an extraordinary simplicity and speed, which make it convenient and promising. Apparently, this method can also be applied successfully to other semiconductor materials.

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Note: Figure translations are in progress. See original paper for figures.