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STUDY OF THE INHOMOGENEITIES OF OVERCOMPENSED SILICON SAMPLES DOPED WITH MANGANESE

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Inhomogeneities in the near-surface region of diffusion-doped silicon with manganese atoms were studied using the local photo-EMF method and photovoltage and photoconductivity signals were detected. It has been established that the inhomogeneous region is located at a depth of 3÷35 µm from the surface of the crystal. The magnitude of photo-EMF in these layers does not change monotonically from point to point. It was revealed that the photo-EMF spectra depend on the wavelength of the irradiated light, while the shape of the areas and their shift are related to the penetration depth of laser radiation. The photo-EMF signal increases to a depth of ~25 µm from the surface, then saturates and from ~30 µm smoothly decreases and completely disappears at a depth of ~40 µm. The magnitude of the internal electric field was determined using the Tauc method. A model of the structure of the near-surface region of diffusion-doped silicon with manganese is proposed.
Key words: *Diffusion; Inclusion; Heat Treatment; Inhomogeneity; Photo-EMF; Photoprobe; Scattering; Gradient; Twin*
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INTRODUCTION

In recent years, for the controlled formation of the defect structure of silicon, so-called unconventional impurities have been used - impurities of T-ions (transition elements), which create a number of deep levels in the band gap of silicon. These specially introduced impurities interact with various uncontrolled impurities during technological treatments [1-5].

This work presents the results of a study of the inhomogeneity of the surface layer of silicon formed during its diffusion doping with manganese atoms. It was revealed that high-temperature heat treatment contributes to the formation of an anomalous profile of the distribution of current carrier concentration, characterized by a sharp decrease in the latter to a depth of 30-50 µm from the surface of the crystal. This layer requires comprehensive studies of the mechanism of impurity entry into the crystal volume and their interaction with both the matrix (main) atoms of the crystal and with technological (background) impurities, as well as with structural defects [6-10].

EXPERIMENTAL PART

To determine the inhomogeneity, the local photoprobe method and the method of small-angle laser radiation scattering were used. These methods make it possible to identify heterogeneous areas with high accuracy, especially areas with large conductivity gradients.

Using the local photovoltage method, inhomogeneities were studied in the original, heat-treated and control silicon crystals and doped Si <Mn> crystals having the shape of a rectangular parallelepiped of various sizes: (0.3÷0.5)×(0.3÷1.6)×(0, 5÷1.6) cm^3.

The study was carried out on a sample with different surface conditions after each layer removal. There were basically two types of surface: 1-surface obtained after mechanical processing with M14, M7 and M4 powders, after etching for 40-60 seconds, in boiling alkaline etchant (H_2O_2:NaOH = 1:3) followed by washing in double-distilled water [10].

Due to the fact that the formation of twins in the original single-crystal silicon leads to a change in the orientation of the crystal, a method was used to determine surface defects when it was illuminated. It is known that a twin is a region of a crystal whose orientation is a mirror image of the main crystal (twin orientation). A characteristic feature of a twin is the presence of a flat boundary, which on the side surface of the crystal is the line of intersection of the twin plane with the surface. On the cut plane, the twin boundary appears as a straight line.

Crystals that had no grain boundaries, twins, or twin lamellas were selected for the study.

Photoconductivity and photovoltage measurements [12,13] were carried out at room temperature on Si <Mn> samples in which the bulk part of the crystal was overcompensated, i.e. n -type. The dimensions of the samples were as follows: after doping with metal atoms - 0.3×0.4×0.5 cm^3 and 0.4×1.6×1.6 cm^3, after cutting to study the photovoltage - 0.15×0,3×0.5 cm^3 and 0.3×1.5×1.6 cm^3.

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To determine the heterogeneous areas, these samples were cut out as shown by the dashed lines in Fig. 1. Samples cut in this way made it possible to compare the photoconductivity and photovoltage both from the cut surface of the samples.

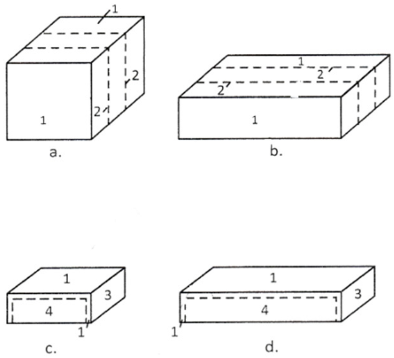

Figure 1. Type of sample Si <Mn>, Si<Co>, Si<Cr> for studying photovoltage and photoconductivity:
a - sample 1 (initial); b – sample 2 (initial); c, d – samples after removal of 50 μm from three faces;
1 - near-surface area 2 - cut line; 3 - ohm contact; 4 - volume area.

RESULTS AND DISCUSSION

Figure 2 shows the results of light scanning for typical Si < Mn > samples when irradiated with light with a wavelength of 0.63 μm, after removing a layer 3-5 μm thick from the surface. It is clear from the figures that the photo-signal does not change monotonically from point to point. Changes in signal magnitude are highly localized. The average value of the photo-signal changes slightly, while in some areas the photo-signal changes greatly. This behavior is associated with a change in the lifetime of current carriers in individual local areas, caused by the inhomogeneity of the crystal.

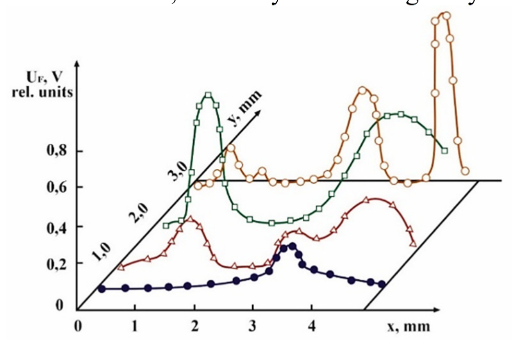

Figure 2. Light scanning results for one sample n-Si<Mn> when irradiated with light with λ = 0.63 μm

In Fig. 3. The results of light scanning are presented for one of the typical Si<Mn> samples at light wavelengths λequal to 0.63 μm, 1.15 μm and 3.39 μm after removing a 5 μm thick layer from the surface. From figure it can be seen that the amplitude of the photovoltage increases with decreasing wavelength of the irradiating light.

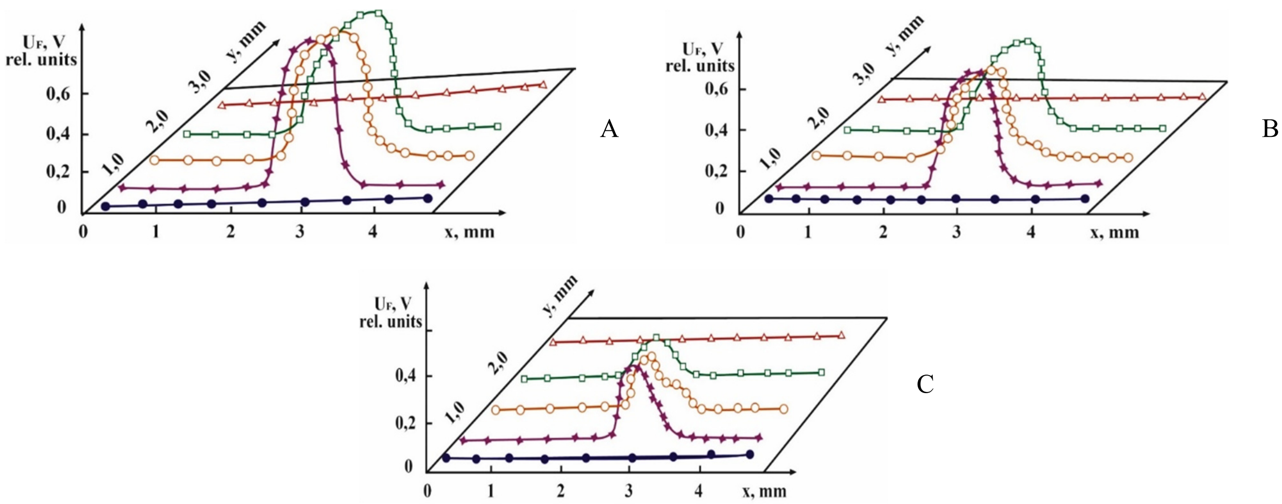

Figure 3. Light scanning results for one sample p - Si < Mn > when irradiated with light of different wavelengths:
A) $\lambda = 63\ \mu m$; B) $\lambda = 1.15\ \mu m$; C) $\lambda = 3.39\ \mu m$.

The dependence of the photovoltage on the thickness of the near-surface layer is shown in Fig. 4. It can be seen that the photovoltage signal increases as the layer is removed to a depth of ~25 µm, and then in a narrow region it saturates and from ~30 µm smoothly decreases and completely disappears after removal above 45÷50 µm.

To determine the internal electric field of the inhomogeneous region of the crystal, an external electric field of E_i polarity, inverse to the internal electric field Ei, was applied to it. Studies have shown that at E = 0.9-1.2 V/cm, the volumetric photovoltage current when illuminated with modulated light is zero. In this case, E_i can be determined according to the expression:

$$E_i \rightarrow \frac{1+b}{2} \cdot \frac{i}{s}, \quad (1)$$

where s is the cross section of the crystal, $b$is the ratio of electron and hole mobilities, i is the compensating direct current, ρ and is the resistivity of the crystal.

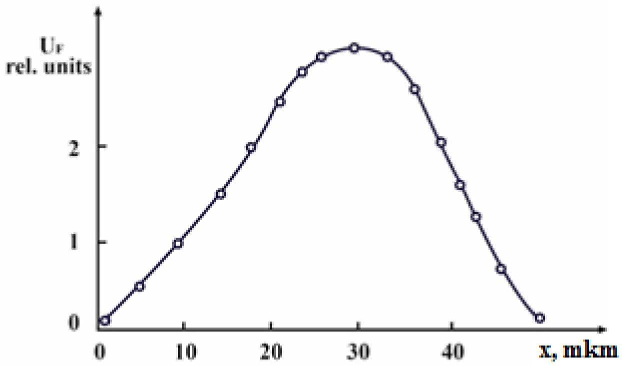

Figure 4. Dependence of the photovoltage on the thickness of the surface layer n - Si < Mn >, T = 300 K, λ = 0.63 µm

When substituting the values into (1) $b = \mu_n/\mu_p = 3, p = 1.3 \cdot 10^4\ Om \cdot cm,\ i = 1.39 \cdot 10^{-6} A,\ s = 2 \cdot 10^{-2} cm^2$ are obtained E_i = 0.8 V/cm.

Based on the results of complex studies, a model of the structure of the near-surface region of diffusion-doped silicon with manganese is proposed. The near-surface region of compensated silicon is a large number of Schottky diodes (pairs), connected in opposite directions, with a layer of silicon compensated by metal atoms between them, connected in parallel and in series (Fig. 5).

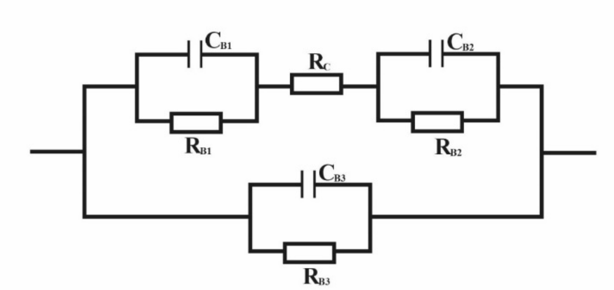

Figure 5. Model of the structure of the near-surface region of diffusion -doped silicon with manganese, chromium and cobalt atoms. R_C – resistance of the compensated area, C_B, R_B – capacitance and resistance of the Schottky barrier, respectively.

This model is determined by the island nature of the inclusions of the second phase, located at a depth of ~3-45 µm from the surface. This is also confirmed by the maximum value of the photovoltage at a depth of ~25-30 µm (Fig. 4), where, apparently, there is an optimal ratio between the number of islands (inclusions) and their surface, giving the maximum total surface area of the silicon-second phase inclusions boundary.

CONCLUSIONS

1. It has been established that photovoltage spectra depend on the wavelength of light, and the area shifts and their shape are related to the penetration depth of laser radiation. It has been shown that when using infrared radiation in the near-infrared spectrum, it is possible to determine inhomogeneities in the crystal volume using the local photovoltage method.
2. A study of the dependence of the photovoltage on the thickness of the near-surface layer of doped crystals showed that the photovoltage signal increases as the layer is removed to a depth of ~25 µm, and then in a narrow region it saturates and from ~30 µm smoothly decreases and completely disappears after removing 40 µm.
3. The possibility of determining the internal electric field in an inhomogeneous region of a doped crystal using the Tauc method has been demonstrated. It was established that in the n-Si <Mn> crystal, when an external electric field E_e = 0.9-1.2 V/cm was applied, the internal electric field had a value of E_i = 0.8 V/cm.

4. A model of the structure of the near-surface region of diffusion-doped silicon with manganese is proposed. The near-surface region of compensated silicon is a large number of Schottky diodes (pairs) connected in parallel-series, with a layer of compensated silicon between them.

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ДОСЛІДЖЕННЯ НЕОДНОРІДНОСТЕ НАД КОМПЕНСОВАНИХ ЗРАЗКІВ КРЕМНІЮ, ЛЕГОВАНИХ МАРГАНЦЕМ

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Методом локальної фото-ЕРС досліджено неоднорідності приповерхневої області дифузійно-легованого атомами марганцю кремнію та зареєстровано сигнали фотоелектричної напруги та фотопровідності. Встановлено, що неоднорідна область розташована на глибині 3÷35 мкм від поверхні кристала. Величина фото-ЕРС в цих шарах не змінюється монотонно від точки до точки. Виявлено, що спектри фото-ЕРС залежать від довжини хвилі опромінюваного світла, а форма ділянок і їх зсув пов'язані з глибиною проникнення лазерного випромінювання. Сигнал фото-ЕРС зростає до глибини ~25 мкм від поверхні, потім насичується і від ~30 мкм плавно спадає і повністю зникає на глибині ~40 мкм. Величину внутрішнього електричного поля визначали методом Таука. Запропоновано модель структури приповерхневої області дифузійно легованого кремнію марганцем.
Ключові слова: *дифузія; включення; термообробка; неоднорідність; фото-ЕРС; фотозонд; розсіювання; градієнт; двійник*