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# The Energy Spectrum of Defects in Silicon, Doped with Vanadium

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***Abstract*— In this work, using the methods of capacitance spectroscopy of the studied energy range of deep levels of vanadium and it is shown that the vanadium in silicon creates deep levels Ec − 0.45 eV and Ec − 0.52 eV and Ev +0.41 eV, depending on the type of conductivity of the initial silicon and the cooling rate of the sample after diffusion, and the level of Ec − 0.22 eV is a defect in the heat treatment. Performed a systematic analysis of the results on the study of silicon doped with vanadium. It is shown that the atoms of vanadium in silicon created a number of deep levels with different ionization energies.**

***Index Terms*— silicon, spectroscopy, the energy spectrum of a deep level, doping, impurity, vanadium.**

## I. INTRODUCTION

The semiconductors used for the manufacture of semiconductor structures, should have a specific resistivity (ρ) in the temperature range (ΔT). In terms of technology obtaining a semiconductor with a wide range of parameters difficult. Required parameters, particularly high resistivity, to some extent can be obtained by doping with impurities creating deep levels. From this point of view, the silicon alloying with vanadium is of scientific and practical interest. According to preliminary data, the vanadium can give a range of parameters depending on the technological process of doping [1-6]. As noted in [1], depending on the resistivity of the original silicon, its resistivity can be changed to three or four orders of magnitude.

This paper is devoted to a systematic analysis of the results on alloying silicon with vanadium. Consider two kinds of manufacturing technology of silicon samples with vanadium.

### Silicon doped with vanadium from the sputtered layer.

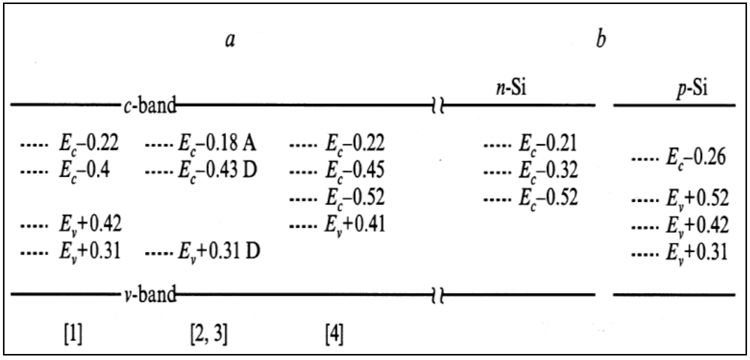
In this method [2] diffusion of vanadium in silicon were carried out from the deposited metal layer of V at a temperature of 1200÷1250 °C for 2÷20 hours with subsequent cooling in air. As starting material used n-type silicon and p-type with a resistivity of 5÷100 Ohm.cm. Their resistivity after the process of diffusion was increased, indicating the formation of both donor and acceptor levels. To conduct research on samples n-Si<V> was formed by the Schottky barriers by deposition of gold in vacuum. The samples p-Si<V> diffusion of phosphorus at a temperature of 1250°C for 30 minutes was obtained p-n-transitions.

### Photo capacitive characteristics.

Measurements of the spectra of photo capacity (PhC) and photoconductivity (PC) was carried out at a temperature of 77 K. As a monochromator was used the IRM-1 with a NaCl prism. According to various authors [1-6], the vanadium in the n-Si creates deep levels only in the upper half of the forbidden zone, and in silicon p-type in both the upper and the lower halves of forbidden zone (see table 1).

As noted in [2] with the increase of boron concentration in silicon of the p-type concentration of the vanadium centers are reduced, and silicon is n-type with increasing concentration of phosphorus concentration of the vanadium centers is increasing.

Table 1. The ionization energy levels of vanadium in silicon: a-data of works [1,3-5] and b-the results of [6].



## II. SILICON DOPED WITH VANADIUM CHLORIDE VANADIUM.

In this method [1], the silicon doping with vanadium produced by diffusion of the deposited on the surface of the silicon layer of vanadium chloride in the open air at 1200°C for 3-24 hours. The maximum rate of cooling after the diffusion of vanadium was at throwing samples into the oil ($\upsilon = 300$ K/s), minimum in cooling in the switched off furnace ($\upsilon = 25$ K/s). For research specimens have been fabricated with p+-n-transition.

### Electrophysical and photo-capacitive characteristics.

After the diffusion of vanadium in n-Si with initial resistivity of 5÷20 Ohm.cm at temperature diffusion $T_{diff}$= 900÷1250$^0$C for 2÷100 hours, the conductivity type remained unchanged, and the resistance at temperatures of 300 and 77 K were not changed. On these samples were carried out complex investigations of properties of Si<V> by methods of deep levels transient spectroscopy (DLTS), photo capacitance and photoconductivity.

In samples n-Si with specific resistance greater than 200 Ohm.cm after the diffusion of vanadium resistivity at 300K decreased 3-4 times, and upon cooling to 77 K the resistivity was increased by 3-4 orders. In the samples of silicon p-type with resistivity 5-10$^3$ Ohm.cm after the diffusion of vanadium type conductivity changed, that is to

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create donor and acceptor levels. While the resistivity at 300 K took values from $10^2$ to $10^4$ Ohm.cm.

Measurements of the spectra of photoconductivity (PC) of the samples Si<V> found that the spectral dependence of the PC, there are several distinct steps in hν~ 0.21, 0.44 and 0.52 eV, which indicates formation of several deep levels in these samples (Fig.1, curve 1). As follows from the spectra of photoconductivity, in p-Si, which after the introduction of vanadium goes to n-Si, the long wavelength boundary of PC lies in hν~ 0.41 eV, and the growth of photo response in the field hν~0.65 eV is associated with the double optical transitions via this or other deep levels. Measurement of PC with its own illumination showed that the changes of spectra are observed.

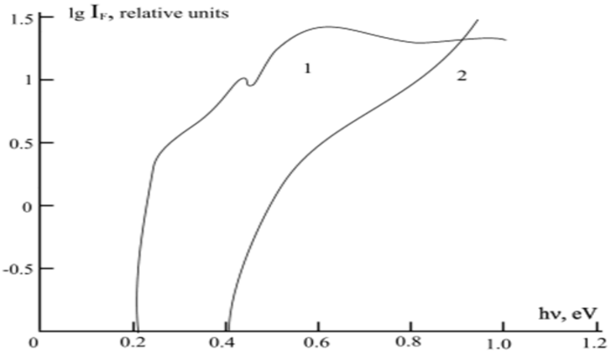

*Fig. 1. Normalized to a constant stream of quanta spectra of* photoconductivity

*n-Si<V> (1) and p-Si crossed to n-Si after the diffusion of vanadium (2)*

*(at 77K)*

The ionization energy of various levels of vanadium in silicon, defined in [1], are given in table 2.

Table 2. The ionization energy levels of vanadium in silicon [1].

| Deep levels | $E_i$, eV | $\sigma \cdot 10^{14}$, cm2 | | $N \cdot 10^{-13}$, $cm^{-3}$ cooling rate, K/s | |
|---|---|---|---|---|---|
| | | $\sigma_n$ | $\sigma_p$ | 10 | 100 |
| A | $E_c - (0.22 \pm 0.01)$ | 1−5 | — | 0.2 | 6.7 |
| B | $E_c - (0.45 \pm 0.01)$ | 1−6 | — | 0.7 | 4.4 |
| C | $E_c - (0.52 \pm 0.03)$ | 2−20 | — | 0.5 | 0.6 |
| M | $E_v + (0.41 \pm 0.02)$ | — | 4−25 | 0.5 | 0.5 |

To identify additional levels of vanadium in silicon samples n-Si<V>, we also carried out measurements of the spectra DLTS and photo capacitance. In

In Fig.2 shows typical DLTS spectra of silicon samples doped by vanadium followed by rapid cooling. From measurements of the DLTS spectra in the constant voltage mode in silicon samples doped with vanadium and subsequent processing of spectra of the detected deep levels with fixed ionization energy $E_C$ -0.22 eV, $E_C$–0.45 eV, $E_C$–0.52 eV and $E_V$+0.41 eV with a capture cross section of charge carriers $\sigma_n = 5 \cdot 10^{-14}$ cm$^2$, $6 \cdot 10^{-14}$ cm$^2$, $2 \cdot 10^{-15}$ cm$^2$ and $\sigma_p = 2.5 \cdot 10^{-13}$ cm$^2$, respectively. Analysis of the results showed that the efficiency of the formation of deep levels in samples of n-Si<V> increases with increasing temperature diffusion and cooling rate ὺ after the diffusion.

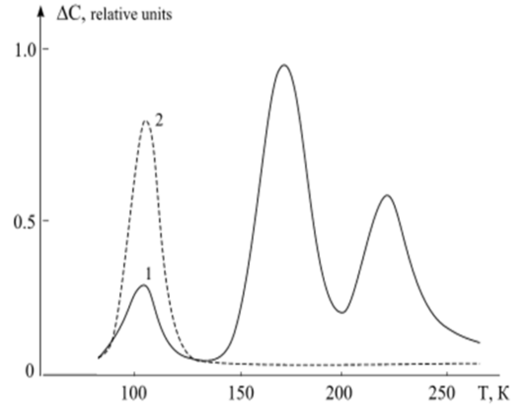

Fig.2. Typical DLTS spectra of the samples n-Si<V> - curve 1 control samples (heat-treated n-Si) - curve 2.

Fig.3 (curve 1) illustrates the typical range of capacitance on n-Si<V> immediately after the diffusion, which shows that the spectrum consists of three steps of different sizes. This suggests that in n-Si<V> formed by the three deep levels with fixed energy of ionization, $E_C$–0.22 eV, $E_C$–0.45 eV and $E_C$–0.52 eV. In region hν > 0.6 eV there is a smooth increase of capacity. In the control samples of n-Si (without vanadium), passed a similar heat treatment was detected only levels of $E_C$–0.22 eV, which is characteristic for heat treatment defects, their concentration was of the order of $N_{DL} = 10^{12}$ cm$^3$.

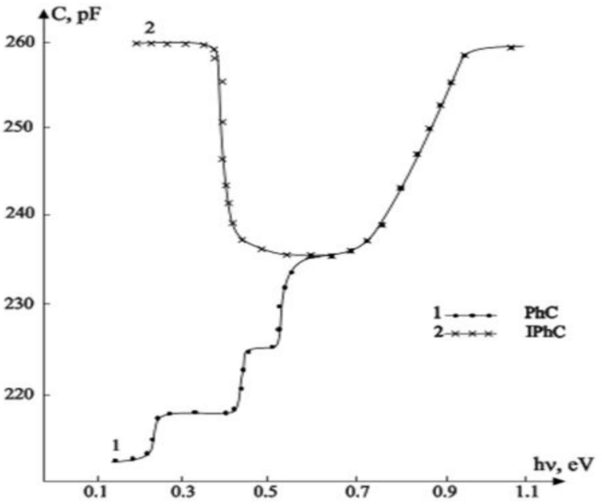

*Fig.3.Typical spectra photo capacitance (1) and photo-induced*

*capacitance (2) diodes of the n-Si<V>.*

As can be seen from Fig.1, Fig.2 and Fig.3 vanadium in silicon creates deep levels $E_c - 0.45$ eV, $E_c - 0.52$ eV and $E_v$ +0.41 eV, depending on the type of conductivity of the initial silicon and the cooling rate of the sample after diffusion, and the level of $E_c - 0.22$ eV is a defect in the heat treatment.

A comparison of the DLTS spectra, photo-capacitance and photo conductivity showed that the thermal and optical ionization energy deep levels of vanadium in Si, within the error of the experiment are the same.

## CONCLUSION

Thus, atoms of vanadium in silicon created a number of deep levels with different ionization energies [1-6], thus all available data are somewhat scattered and contradictory. It should be noted that the levels of vanadium in silicon gives the structure on the basis of its sensitivity to optical radiation and deformation and also enables to obtain a diode structure with a nonlinear S-shaped current-voltage characteristic, which is very important for the realization of optical bistable devices. While changing the duration of diffusion can be controlled by the concentration of electrically active centers that provides controlled sensitivity to external influences.

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