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Jump Mechanism of Electric Conduction in n-Type Silicon Implanted with Ne^{++} Neon Ions

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The article presents the results of research on alternating-current electrical conduction in phosphorus-doped silicon, strongly defected by the implantation of Ne^{++} neon ions. An analysis of electrical properties recorded at the annealing temperature of $T_{\mathrm{a}} = 373$ K and affected by the changes of testing temperature ranging from 253 K to 368 K as well as frequency from 50 Hz to 5 MHz has been discussed. The obtained results have confirmed the occurrence of two conduction mechanisms in strongly defected semiconductors: the band conduction mechanism that is characteristic of low frequency values and the jump conduction one that corresponds to higher frequencies.

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1. Introduction

The research has been carried out on phosphorus-doped silicon of $\rho = 0.25$ Ω cm resistivity, implanted with Ne^{++} ions of the $E = 100$ keV energy and a fluence of $D = 2.2 \times 10^{-14}$ cm^{-2}. The samples have been isochronously annealed for the time of 15 min, within the T_{a} temperature range from 323 K to 873 K, with an average increase rate of 50 K. The values of measured electrical parameters (C_p, σ) have been recorded within the T_p temperature range from liquid nitrogen temperature (LNT) to 373 K and at the frequencies ranging from 50 Hz to 5 MHz.

The article presents the results obtained for the annealing temperature of $T_{\mathrm{a}} = 373$ K. Implantation conditions and annealing temperature have been determined on the basis of earlier works [1, 2]. An analysis of temperature dependences of capacity and conductivity has made it possible to estimate the values of conduction activation energy ΔE and defects relaxation time. That allowed to identify types of defects in the tested structure [3] and, above all, to determine electrical conduction mechanisms, which have occurred in the implanted layers.

2. Analysis of the obtained results

In order to prepare a complete analysis of conduction mechanisms in strongly defected n-type silicon, it was necessary to consider the influence of testing frequency (Figs. 1, 2) and annealing temperature (Fig. 3) on conductivity and capacity of the tested sample.

In Figs. 1 and 2 it can be seen that an increase in the testing temperature T_p causes a rise of the σ and C_p values. What is more, for the temperatures higher than 253 K two stages of additional polarization were distinguished, one which corresponds to low frequencies and the other one that is characteristic of high frequencies. They are related to two types of radiation defects that affect the values of measured properties.

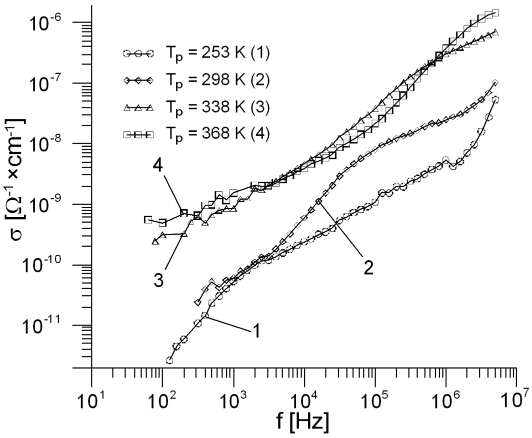

Fig. 1. Conductivity vs. testing frequency for a sample annealed at $T_{\mathrm{a}} = 373$ K.

By analyzing dependences of conductivity on annealing temperature for testing the frequency $f = 1$ kHz (Fig. 3), it was possible to distinguish temperature ranges that correspond to certain processes. At $T_{\mathrm{a}} < 473$ K only insignificant conductivity swings were observed, which means that the charge carrier compensation rate in the allowed energy band is constant and results from a relevant value of radiation defect concentration. For the testing temperatures ranging from 473 K to 573 K conductivity decreases rapidly, e.g. for $T_p = 298$ K it is lower by almost two orders of magnitude. This phenomenon re-

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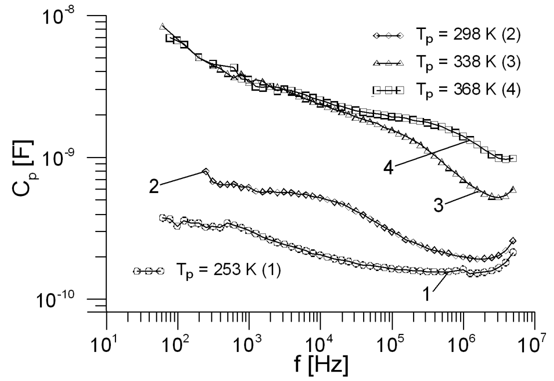

Fig. 2. Capacity vs. testing frequency for a sample annealed at $T_a = 373$ K.

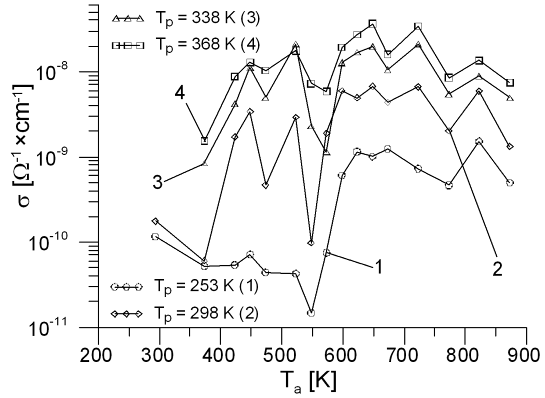

Fig. 3. Conductivity vs. annealing temperature T_a, for the testing frequency $f = 1$ kHz.

sults from the increased value of resultant concentration of deep radiation defects that are so-called trapping centres for charge carriers. Consequently, electron quantity decreases simultaneously causing reduction in the conductivity value σ. For the temperatures above 600 K conductivity returns to its previous level and then decreases insignificantly. This can be caused by annealing of radiation defects which have occurred at lower temperatures and also by the decrease in concentration of such types of radiation defects like Si–P1 and Si–B3 that gradually decay as the annealing temperature rises [3].

Dependences of σ and C_p on the temperature for various frequency values are presented in Fig. 4. They make a basis for estimating the value of conduction activation energy ΔE, which, in turn, can be used for the identification of radiation defects and evaluation of their energies. For that reason, it was necessary to perform a fit of certain parts of characteristics $\sigma_p = f(1000/T_p)$ and $C_p = f(1000/T_p)$ with the function $\ln(y) = Ax + B$. Then, the values of ΔE were calculated according to the formula

$$\Delta E = A \times 1000 \times k\,, \tag{1}$$

where k is the Boltzmann constant.

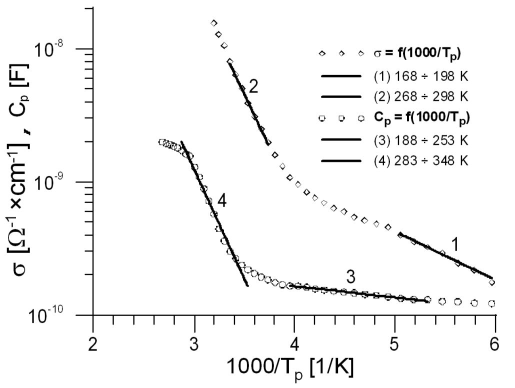

Fig. 4. Conductivity σ and capacity C_p vs. inverted temperature $1000/T_p$, for the testing frequency f = 1 kHz.

TABLE

Activation energy values for the testing frequency $f = 100$ kHz.

Measured parameter	Testing frequency [kHz]	Fitting range	Activation energy [eV]
σ	100	1	0.07
		2	0.31
C_p	100	3	0.02
		4	0.31

The calculated values of the activation energy are given in Table.

As can be seen in Fig. 4 an increase in the value of conductivity is followed by the capacity rise. It means that the charge transfer runs by jump conduction between the radiation defects that originally are in the neutral charge state. As a result of jump recharging a dipole is formed, which causes an increase of dielectric permeability and capacity of the tested sample. On the other hand, electron transfer between the radiation defects brings about conductivity increase.

High values of activation energy, calculated on the basis of capacity and conductivity (Table) mean that jump conduction runs over the potential barrier of the radiation defects. Those values also indicate the position of natural defect energy bands regarding the bottom of the conduction band. According to the Mott theory [4], in the case of electrical jump conduction, a value of conductivity is the function of frequency and can be described by the following formula:

$$\sigma \sim f^{\alpha}\,. \tag{2}$$

With the use of analytical methods together with the characteristics presented in Fig. 1, the values of frequency coefficients α were calculated and are shown in Fig. 5.

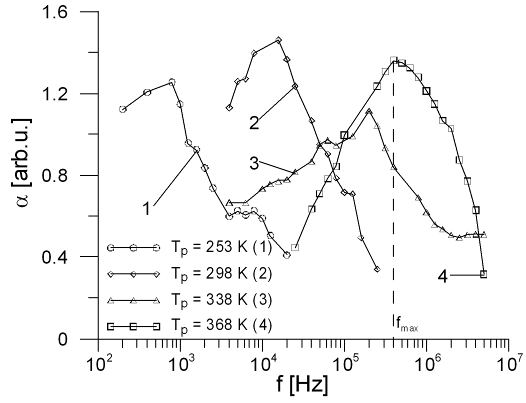

Fig. 5. Frequency coefficient α vs. testing frequency for the annealing temperature $T_\mathrm{a} = 373$ K; f_max — testing frequency value that represents a local maximum of the presented function.

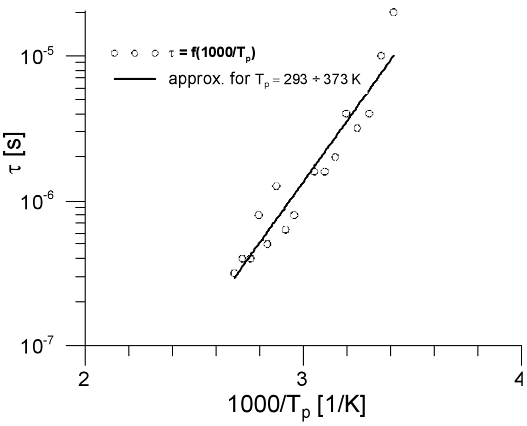

Fig. 6. Relaxation time τ vs. $1000/T_p$ at $T_\mathrm{a} = 373$ K.

As proved in [5], over the time τ from the moment of dipole formation an electron from a negative defect can return to a positive defect, which corresponds to high-frequency conductivity, or leave a positive defect, which results in direct-current electrical conductivity. Based on the frequency f_max, from the $\alpha(f)$ characteristics shown in Fig. 5, the time τ value can be calculated, according to the formula

$$\tau \approx 1/\omega = 1/(2\pi f)\,. \tag{3}$$

Activation energy calculated with the use of the time τ dependence on the inverted temperature $1000/T_p$ (Fig. 6), determines the band energy of negatively charged defects.

The approximation presented in Fig. 6 covers the T_p temperature range from 293 K to 368 K. The measured characteristic was fitted by the function $\ln(y) = Ax + B$ and then according to formula (1) the value of jump conduction activation energy was estimated, which is $\Delta E = 0.42$ eV.

3. Conclusions

The article presents the results of research on strongly defected n-type silicon which are analyzed from the viewpoint of various mechanisms of electrical conductivity.

Strong dependence of electrical properties on the sample annealing temperature was observed. It was confirmed that the mentioned dependence is caused by the changes in the concentration values for various types of radiation defects. Those changes are correlated with specific values of annealing temperature.

It was established that two types of radiation defects are responsible for the increase of conductivity and capacity values within the testing temperature range from 253 K to 368 K. For those defects it was possible to determine the band energies for the neutral and negative charge states.

References

[1] P. Żukowski, J. Partyka, P. Węgierek, *Phys. Status Solidi A* **159**, 509 (1997).

[2] J. Partyka, P. Żukowski, P. Węgierek, A. Rodzik, Y. Sidorenko, Y. Szostak, *Semiconductors* **36**, 1326 (2002).

[3] R.C. Newman, D.N.J. Totterdell, *J. Phys. C., Solid State Phys.* **8**, 3944 (1975).

[4] N.F. Mott, E.A. Davis, *Electronic Process in Non-Crystalline Materials*, Clarendon Press, Oxford 1979.

[5] P. Żukowski, T. Kołtunowicz, J. Partyka, P. Węgierek, M. Kolasik, A.V. Larkin, J.A. Fedotova, A.K. Fedotov, F.F. Komarov, L. Vlasukova, *Przegląd Elektrotechniczny* **3**, 247 (2008) (in Polish).