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SHORT COMMUNICATION

CONDUCTION VIA DEEP LEVELS IN Si p-n JUNCTIONS PREPARED BY DIRECT LASER IMPLANTATION OF PHOSPHORUS

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The forward current in Si n^+p diodes prepared by direct laser implantation of phosphorus is studied as function of temperature within the range (77-295) K. It is shown that the current does not depend on the temperature up to (125-130) K. Trap assisted tunneling in these diodes is suggested as the main conduction mechanism.

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1. Introduction

The Si p-n junctions play an important role in the rectifier and switching diodes. These junctions are essential elements in the bipolar discrete transistors and integrated circuits. The elucidation of the conduction mechanism in p-n junction diodes is important for characterization of charge transfer in the doped semiconductors, for proper understanding of the electrophysical parameters of the p-n junction diodes. It is well known that the current of p-n junction diodes at temperatures of 300 K and above is caused by recombination of the injected excess minority carriers either in the bulk of adjacent p and n regions or in the space charge layer at the p-n boundary. If this recombination remains the dominant transport mechanism at $T<300\ K$, the pre-exponential terms of the forward I-V characteristics should be not exactly linear to $\exp(-E_g/kT)$ in the case of bulk recombination or to $\exp(-E_g/2kT)$ for space charge recombination of excess minority carriers (E_g is the forbidden gap energy). Consequently, the forward I-V characteristics measurements of Si p-n junction diodes within temperature range (77-295) K and the evidence of substantial deviations of the temperature dependence of the preexponential term of forward I-V characteristics from linear dependence to $\exp(-E_g/kT)$ or $\exp(-E_g/2kT)$ will be unambiguous evidence for the appearance of a different transport mechanism.

2. Experimental

Boron-doped single crystalline Si (111) (with a characteristic resistivity of 10 Ωcm) was evenly covered with a 10 μm-thick layer of an emulsion containing P and Si.

The samples were treated in high vacuum ($\leq 10^{-3}$ Pa) with a 10 W CO_2 laser source [1-2]. The treatment was conducted starting with the coated side, while the laser spot extended over the whole sample surface. The power density was 40 Wcm^{-2} and the treatment was prolonged for about half of an hour. After treatment, the samples were cooled in vacuum down to room temperature.

The complete cleaning from residues resulted from emulsion was carried out by a plasma discharge in a jet of oxygen. We prepared three type of diodes hereafter denoted by A, B and C, which slightly differ in terms of exposure times to laser irradiation, of 25, 30 and 35 min, respectively.

The backside of the Si collector was further coated with an Al layer. Once the laser treatment had been completed, we deposited Al dots of 1 mm diameter on the front of the Si substrate, as well.

The forward current of these diodes was measured at different temperatures in the (77-295) K temperature range. During these measurements the diode was placed in a liquid nitrogen thermostat. The temperature was measured with the help of a D220 Si p-n junction diode.

3. Results and discussions

The forward I-V characteristics of the diode type C measured at various temperatures are shown in Fig. 1.

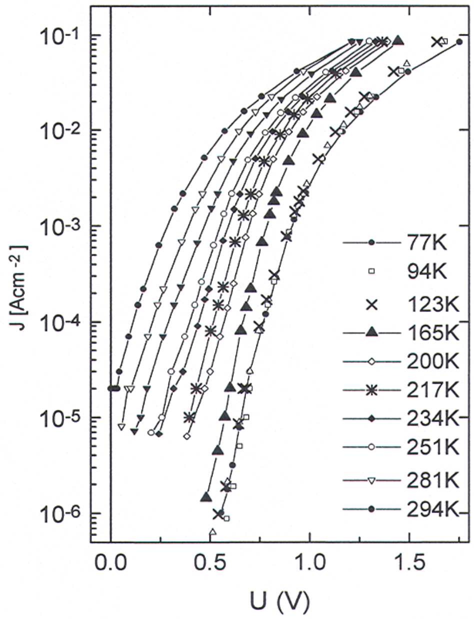

Fig. 1. Forward current density of Si n^+p diode type C (laser exposure time ≅ 35 min), prepared by direct laser implantation, at temperatures labelled on figure.

As is expected when the diode temperature decreases the current for a constant applied voltage also decreases in the (294-123) K temperature range. At 77, 94, 113 and 123K the current practically does not change with changing the temperature. The I-V characteristics of diode types A and B are similar. The currents, measured at 77, 103, 120 and 127 K in diode type A and at 77, 102, 118 and 130 K in diode type B, are also independent on the diode temperature. These results clearly show that the conduction mechanism in the temperature range from 77 to (120-130) K has the characteristics of a tunneling process.

The studied diodes are n^+p type and, because of the low doping concentration $(N_A \approx 10^{15}\ cm^{-3})$ in p type Si substrate estimated from C-V measurements given in Ref. 3 the thickness of the space charge layer (even for the forward bias) is in order of micrometer. Therefore, direct tunneling of electrons through the space charge layer to the Si valence band, as in the case of heavily doped tunnel diodes, should be excluded. The only remaining tunneling mechanism in these diodes can be the trap assisted tunneling or multistep tunneling [4-5]. The laser treatment is applied to the Si substrate side covered with an emulsion containing P and Si. Because of this the traps generated during the laser treatment will be situated predominantly on the *n* side of these laser treated Si $n^+ p$ diodes. In these circumstances one may expect the tunnelling type conduction to be carried out by subsequent tunnelling of the holes from occupied to unoccupied deep levels in the n side of these diodes.

For temperatures above 125 K, for all diodes, the slope of the plot of lg(J) versus the applied voltage, V, and the value of $J_0(T)$, inferred by extrapolating the same plot till the intersection with the current axis at V=0, depend on the temperature. The forward current in p-n diodes is given by the expression $J = J_0\exp(qV/nkT)$ where n is equal to 1 for the case of bulk recombination or it is below 2 for the case of space charge recombination of minority carriers. The values of n calculated by this expression decrease from n in the range of 6-4 at T = 130-140 K to $n \approx 2.2$ at T = 294 K. Therefore the calculated values of n from the measured I-V characteristics are an evidence that diode current at these temperatures is not determined by either bulk or space charge recombination.

The plot of $\ln(J_0/T^2)$ versus $1000/T$ of diodes type A in the (125-295) K temperature range is presented in Fig. 2. From the slope of this plot, an activation energy $E_a = 0.13$ eV was obtained. The slopes of the plots for the diode type B, measured in the temperature range of (118-294) K, and the diode type C, measured in (165-294) K temperature range, results in energy values $E_a = 0.02$ eV and $E_a = 0.37$ eV, respectively. The E_a values in all cases are smaller than $E_{g/2} = 0.55$ eV. This is another evidence that in the corresppondning temperature ranges the diode current is not determined by the recombination of the excess carries in the space charge layer of these diodes. In the case of bulk recombination E_a should be greater than 0.55 eV therefore the bulk recombination is also excluded in these circumstances.

In this case, at these temperatures, the carrier transport via deep levels is a combination of the hole tunnelling between occupied and unoccupied deep levels through the potential barrier between them and the thermally stimulated emission over the same barrier. For this variable range hopping Mott has proposed [6] the conductivity expression $s(T)=s_0\exp[-(T_0/T)^{1/4}]$. This expression is valid for uniform energy distribution of deep levels.

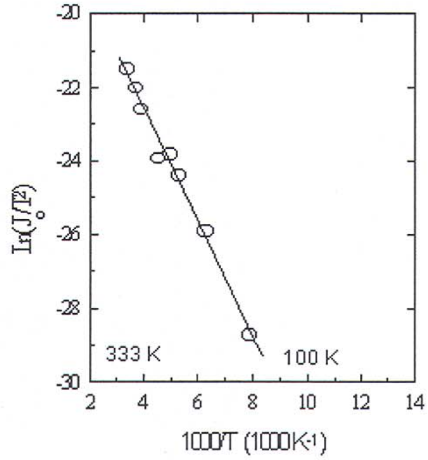

Fig. 2. Plot of $\ln(J_0/T^2)$ vs. 1000/T for Si n^+-p diode type A (laser exposure time ≅ 25 min) prepared by direct laser implantation.

The conductivity of the diode without bias voltage is proportional to $J_0(T)$. Therefore, for the case of variable range hopping J_0 is proportional to $\exp(-(T_0/T)^{1/4})$. The values of $J_0(T)$ given in Fig. 2 are replotted as $\ln(J_0)$ against $T^{1/4}$ in Fig. 3. From the slope of this plot the value of $T_0^{1/4} = 151.52\ \mathrm{K}^{1/4}$ is obtained. Knowing the value of T_0, one may determine the uniform energy distribution N_ε from the equation [7]:

$$N_\varepsilon = 16\alpha^3/kT_0, \tag{1}$$

where

$$\alpha = 2\pi(2m^* E_a)^{1/2}/\hbar \tag{2}$$

For $m^*=0.32\ m_e$ and E_a assumed to be equal to 0.5 eV, $\alpha \cong 2.05\times10^7\ \mathrm{cm}^{-1}$.

The calculation gives $N_\varepsilon = 3\times10^{18}\ \mathrm{cm}^{-3}\mathrm{eV}^{-1}$.

Using the expression proposed by Mott [6] the range of most probable hopping R_m and the energy of this hopping E_m can be obtained:

$$R_m = (9/8\pi\alpha N_\varepsilon kT)^{1/4} \tag{3}$$

$$E_m = [2\alpha^3(kT)^3/9\pi N_\varepsilon]^{1/4} \tag{4}$$

For the diode type A, the values of R_m and E_m measured from the Fermi level position at 150 K are 8.17×10^{-7} cm and 0.14 eV, respectively. Replotting $\ln(J_0(T))$ versus $T^{-1/4}$ for the diodes type B and C the obtained values are $N_\varepsilon = 2.17\times10^{20}$ and 1.3×10^{17} $\mathrm{cm^{-3}eV^{-1}}$, respectively.

These rather high values of N_ε are in accordance with the high density of recombination centers in these diodes. This inference is based on the measured transient behaviour of the reverse currents after the forward pulse voltage cancellation, which are of order of nanoseconds.

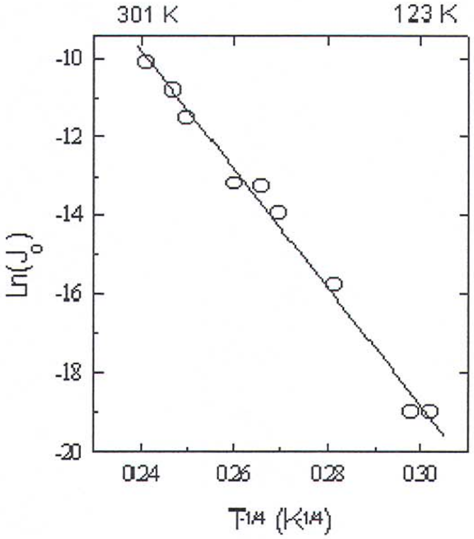

Fig. 3. Plot of $\ln(J_0)$ vs. $T^{-1/4}$ for Si n^+p diode type A (laser exposure time ≅ 25 min) prepared by direct laser implantation.

4. Conclusions

We reported the formation of a quite high density of deep levels in Si n^+p junction diodes prepared by direct laser implantation of P in p type Si substrate with $N_A \approx 10^{15}$ $\mathrm{cm^{-3}}$. The forward current in the (77-125) K temperature range does not depend on temperature. This effect can be assigned to the trap assisted tunneling in these laser prepared diodes. At temperatures between 130 and 290 K, the diode current may be connected with either a thermally stimulated emission of holes from deep levels or with variable range hopping of holes in the same diodes.

References

[1] I. Ursu, A. M. Prokhorov, I. N. Mihailescu, V. Craciun, R. Medianu, Al. Popa, S. G. Kiyak, A. A. Manenkov, G. N. Mikhailova, Appl. Phys. Lett., **51**, 2109 (1987).
[2] M. Bertolotti, M. Rossi, A. Ferrari, V. Craciun, I. N. Mihailescu, I. Ursu, G. N. Mikhailova, A. Dhaul, R. Chandler, Journal of Applied Physics, **71** (7), 5888 (1992).
[3] I. N. Mihailescu, E. György, C. Ristoscu, C. Timus, A. M. Prohorov, G. N. Mikhailova, S. Simeonov, A. Szekeres, E. Kafedjiiska, Romanian Journal of Physics, **43,** 918 (1998).
[4] O. M. Nilsen, J. Appl. Phys., **54**, 5886 (1983).
[5] S. Ashok, P. P. Charma, S. Y. Fonach, IEEE Trans. Electron Dev., **ED-27**, 725 (1980).
[6] N. F. Mott, Phil. Mag., **19**, 835 (1969).
[7] V. Ambegaokar, B. I. Halperin, I. S. Langer, Phys. Rev., **B4**, 2612 (1971).