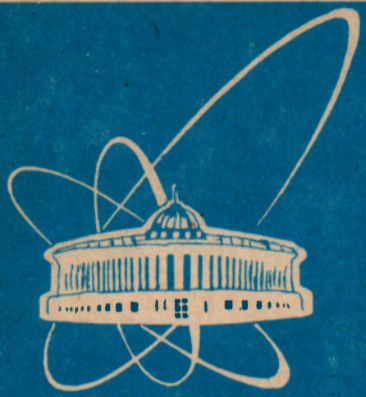

СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E14-96-245

P.Zukowski[1], J.Partyka[1], P.Węgierek[1], D.Mączka,
A.Latuszynski[2]

DIELECTRIC PROPERTIES OF ION IMPLANTED SILICON LAYERS

[1]Faculty of Electrical Engineering, Technical University, 20-618 Lublin, Poland
[2]Institute of Physics, Marie Curie-Sklodowska University, 20-031 Lublin, Poland

1996

Introduction

In the work [1] particular attention was paid to the role of jump recharging in strongly defective semiconductors. Jump recharging leads to dynamic phenomena that cause significant changes in the electric properties of materials with a high concentration of point defects. Among these phenomena, the non-monotonous (step-like) increase in the amorphisation dose accompanied by increase in the ion implantation temperature of silicon [2, 3], as well as the effect of self-restructuring in the course of silicon and CdTe implantation [4], can be listened. The most significant evidence of the influence of jump recharging on the properties of semiconductors is, however, a thermally activated increase in the permittivity of silicon following its irradiation with high neutron doses [5]. The chief point of the phenomenon is that jump charge exchange between two initially neutral defects leads to the formation of dipoles, and as a result, to increase in the polarization of strongly defective silicon..

Ion implantation can be considered, for many reasons, as a very precise and effective method of producing defects in semiconductors and that is why, we decided to investigate the effect of ion implantation on the dielectric properties of silicon. The results of the research are presented in this paper.

2. Methodology

Plates of silicon doped with boron, phosphorus or antimony were implanted with N^+, Ne^+ or Ar^+ ions with 100 keV energy and the ion current density of 0.5 - 1 $\mu A/cm^2$, in doses from $5 \cdot 10^{13}$ to $2 \cdot 10^{15}$ cm^{-2} at room temperature [6]. In the next step these plates were used as capacitors and the implanted layers of high resistivity served as dielectrics. The non-defective silicon layer formed one of the capacitor plates and the other plate was obtained by applying silver paste onto the surface of the implanted layer. The resistance of the implanted layer, as well as the capacity and loss tangent of the capacitors, were measured by means of a digital meter at the frequencies of 0.1; 1.0; and 10 kHz. In the course of measurements the temperature of samples was 20^0C. Next, the samples were subjected to thermal annealing. The annealing duration at each of chosen temperatures was 15 min. The values of the capacity of the capacitors were referred to the surface unit area of $1mm^2$. The experimental error of the measured values of the C capacities were estimated as no more than 7-10%.

3. Results and discussion

The experimental results are shown in Figs 1-4. Figure 1 presents dependences of the unit capacity C (Fig.1a) and the loss tangent tgδ (Fig.1b) on the annealing temperature for the samples doped with boron (resisitivity ρ = 0,03 Ohm·cm), phosphorus (ρ = 10 Ohm·cm) and antimony (ρ = 0,01 Ohm·cm) and implanted with Ar^+ ions in doses $D = 2 \cdot 10^{14}$ cm^{-2} . As can be seen from Fig. 1a, the capacity vs. annealing temperature T_a curves have similar shapes.

The largest unit capacity was obtained for the plates doped with boron at $T_a \approx 300^0$C. Difference of the samples doped with various chemical elements is more evidently illustrated by the curves of $tg\delta = f(T_a)$.

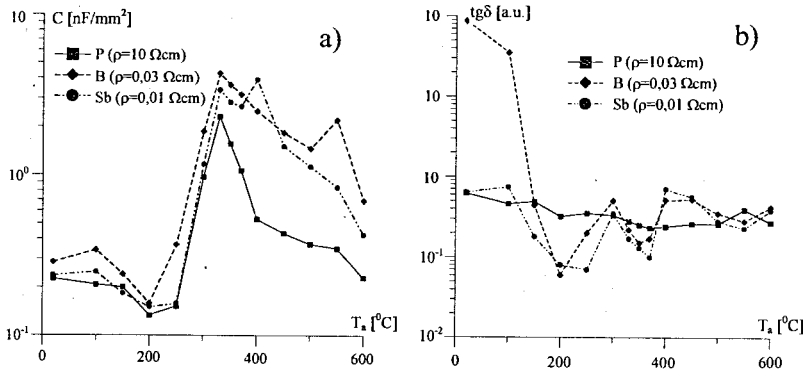

Fig. 1. The dependences of the unit eapacity C (a) and the tgδ (b) of the silicon layers doped with phosphorus, boron or antimony and implanted with Ar^+ ions, E= 100keV, j = 0,5 μA/cm², D = $2x10^{14}cm^{-2}$,on the temperature of isochronous annealing of 15 min. duration (the lines are only to guide the eye)

In Figure 2, the $C=f(T_a)$ and $tg\delta=f(T_a)$ dependences for the silicon plates doped with boron (ρ = 0,03Ohm·cm) and implanted with N^+, Ne^+ or Ar^+ ions in doses of $2 \cdot 10^{14}cm^{-2}$,are presented.

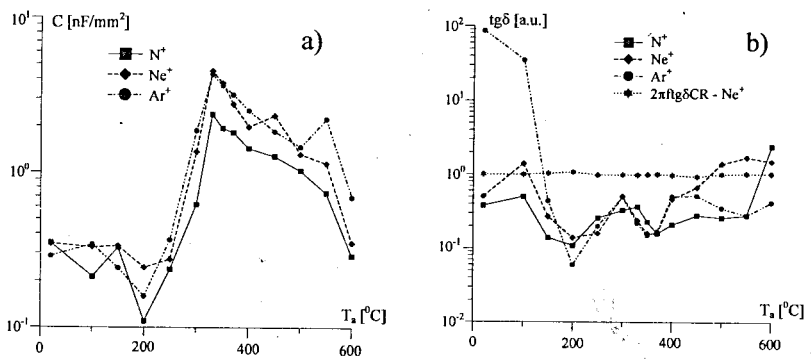

Fig. 2 .The dependences of the unit capacity C (a) and the tgδ (b) of the silicon layers doped with boron and implanted with ions: N^+, Ne^+, Ar^+, E= 100keV, j = 0,5 μA/cm², D = $2x10^{14}cm^{-2}$,on the temperature of isochronous annealing of 15 min. duration (the lines are only to guide the eye).

The analysis of the data shown in Figs 1 and 2 points to existence of two regions of annealing temperatures over which the behavier of the $C=f(T_a)$ and $tg\delta=f(T_a)$ curves differs significantly depending on the investigated region. From 20 to 200°C a slight decrease in the unit capacity and a much stronger drop of tgδ can be observed. At these temperatures the largest changes in C and tgδ occur in the silicon doped with boron and the smallest, in the silicon doped with phosphorus. The type of implanted ions influences just slightly the changes in C but produces a much stronger effect on tgδ (Fig.2). The other region of the annealing temperatures (T_a > 200°C) shows a dramatic increase in the C capacity which reaches its maximum at $T_a \approx 330$°C (Figs 1a and 2a).

Quantitative explanation of the measured dependences of $C=f(T_a)$ and $tg\delta=f(T_a)$ remains the subject of our current research and also requires an additional detailed study. Below we shall only give a restricted qualitative description of the observed phenomena.

As is well-known, in silicon samples ion implantation results in numerous radiation defects different in type and electric charge. Due to this, the permittivity of the irradiated silicon increases. In order to reduce both defect concentration and the permittivity, the samples are always annealed at elevated temperatures. However, along with increasing of the annealing temperature, an opposite effect is often achieved, e.g. increase in the sample permittivity. For instance, such effect takes place in silicon in the conditions of high defect concentration. The phenomenon was explained by us as a result of a jump electron exchange between two nearest defects [1]. If these defects are initially in the neutral state, the electron exchange leads to formation of electric dipoles, and finally to increase in the permittivity. These dipoles are responsible for additional polarization of the defective silicon. As they are not stable, their orientation does not require additional energy of the external electrical field [10].

Figure 1a shows that, along with the annealing temperature, in the temperature range up to ~200°C the capacity of the capacitors decreases. This means that in our experimental conditions, the process of defect annealing dominates over the formation of the dipoles. According to the data from [7] in the considered range of temperatures the annealed defects are mainly the divacancies and the Si-P3 defects. The divacancies are in neutral state and can forme the dipols.

However, defects of the Si-P3 type are the interstitial sites and have the positive charge. Thus, the jump charge exchange between them does not cause formation of additional dipoles and finally, increase in the permittivity. This only leads to the jump conductivity of the defective silicon. Due to this effect the capacitor losses, as well as the values of tgδ must diminish. The dependence of tgδ on the kind of implanted ions at T_a <200°C seems to support this conclusion. The threshold energy of generation of the Si-P3 defects is comparatively high [5], and the probability of their formation should grow with

mass of the implanted ions (N^+, Ne^+, Ar^+). Exactly the same sequence of the tgδ drops was measured in our investigation (Fig.2b).

The performed studies have also shown that in the first region of annealing temperatures the values of tgδ depend on the kind of impurities existing in the silicon samples (Fig.1a). It seems to us that this effect may be attributed to the phenomenon observed in [8], namely, during implantation part of impurity atoms leaves the lattice point positions and then, occupy internodal ones. As a results of these displacements, changes in the capacitor conductivity, as well as in the tgδ values, must occur. Figure 1b showes that tgδ reaches its highest values in silicon samples doped with boron. This is in good agreement with the above consideration, because the atoms of this chemical elements get displaced from the lattice nodal positions more quickly than those of phosphorus or antimony [8].

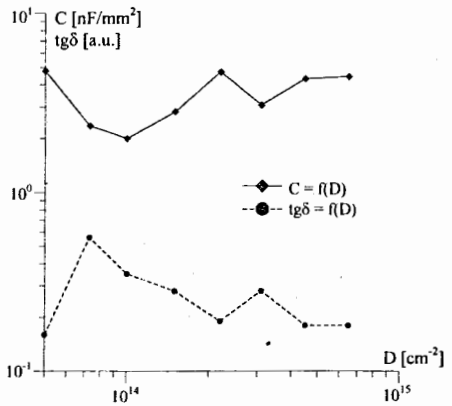

Fig. 3.The dependence of the unit capacity C and tgδ of the silicon doped with boron on the Ne^+ ion implantation doses, E= 100keV, j = 0,5 μA/cm² . (the lines are only to guide the eye).

The second region of annealing temperatures (T_a > 200°C) is more interesting from the point of view of future applications. In this region a dramatic increase (by a factor of 20-30)in the capacity of capacitors occurs. This gives some possibilities to use strongly defective silicon for the production of capacitors for integral systems.In the considered range of temperatures a rapid growth of the interstitial concentration of Si-B2 type was reported [9]. As these defects are in the neutral states - in our opinion - the jump charge exchange between them leads to increase in the permittivity as a result of dipole formation. Further decrease in C along with T_a can be explained by the effect of the domination of Si-B2 defect annealing over dipole generation.

. In the second range of temperatures, especially above 330°C, the influence of the mass of implanted ion on the silicon dielectric properties is well seen. Several phenomena could be responsible for such behaviour of the curves (Fig.2a). The most probable one is the following. The implantation of Si samples was performed at constant ion energy, E=100 keV. This implies that the thickness of silicon defective layers L must be the largest for N^+

and the smallest for Ar^+ implantations. This is in good agreement with the data shown in Fig.2a, as the C capacity is inversely proportional to L.

Figure 3 presents the dependences of the unit capacity C and tgδ on the dose of Ne^+ ions at T_a=330°C. At this temperature the C capacity reaches its maximum value. Also the above mentioned figure shows that changes in C and tgδ following one dose of implantation proceed in an almost mirror-reflection symmetry. This can be a good evidence of the same mechanism of the effect, namely, the jump recharging is responsible for both the capacity changes and the capacitor losses. In particular, the capacitor losses are the result of jump conduction, e.g. jump transfer of charges between defects.

If one assumes that capacitor losses occur only due to the changes of the sample conduction , a simple aritmetical calculation yields the following formula:

$$2\pi ftg\delta CR = 2\pi f\varepsilon\varepsilon_0\rho = 1 \qquad (1)$$

where **f** denotes the applied frequency of the digital meter, **C** and **R** are the capacity and the resistance of the capacitor, respectively.

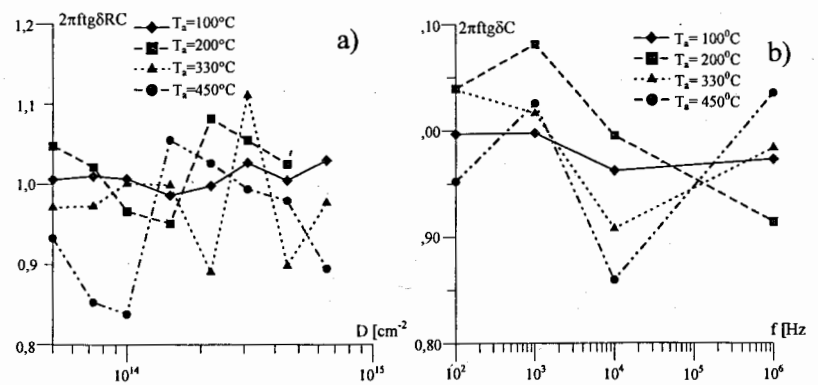

Fig.4. 2πftgδRC as a function of the implantation dose and the measuring frequency of the digital meter . Silicon was doped with boron and implanted with Ne^+ ions. The annealing temperatures were: 100°C, 200°C, 330°C, 450°C (the lines are only to guide the eye).

Figure 4 shows that within errors of no more than ±15%, the obtained results are in good agreement with Eq.1. This means that in the considered capacitors made of implanted Si layers of high resistance, no additional mechnisms causing losses, e.g. relaxation losses, exist. The absence of such relaxation losses was also noted in our earlier study [10].

Acknowledgement

This work was supported by the Comittee of Scientific Research, Poland, under Contracts No 8T11B05509 and No 3P40703205.

References

[1] P. ŻUKOWSKI, S.B. KANTOROW, D. MĄCZKA and V.F. STELMAKH, phys. stat. sol. (a) 112, 695 (1989).

[2] P. ŻUKOWSKI, Sov. Phys. Semicond. 26, 84 (1992).

[3] P. ŻUKOWSKI, K. KISZCZAK, D. MĄCZKA and A. LATUSZYNSKI, Radiat. Eff. 132, 11 (1994).

[4] P. ŻUKOWSKI, Sov. Phys. Semicond. 27, 789 (1993).

[5] Y.H. LEE, N.N. GERASIMENKO and J.W. CORBETT, Phys. Rev. B14, 4506 (1976).

[6] D.MACZKA, A.LATUSZYNSKI, R.KUDUK, J.PARTYKA, Nucl.Instr and Meth. B21(1987)512.

[7] L.J. LEE and J. LORI, Phys Rev. 171, 856 (1968).

[8] N.I. BEREZHNOV, A.R. CHELYADINSKII, M. JARDAN, Y.R. SUPRUN-BIELEVICH, Nucl. Instr. and Meth. B73, 357 (1993).

[9] K.L. BROWER, Phys. Rev. B14, 872 (1976).

[10]P. ŻUKOWSKI, S.B. KANTOROW, K. KISZCZAK, D. MĄCZKA, A. RODZIK, V.F. STELMAKH and E. CZARNECKA-SUCH, phys. stat. sol. (a) 128, 117 (1991).

Received by Publishing Department
on July 5, 1996.

Жуковский П. и др. E14-96-245

Диэлектрические свойства ионно-имплантированного кремния

Представлены результаты исследований изменений диэлектрической проницаемости кремния под действием ионной имплантации (ионы N^+, Ne^+ и Ar^+) и термообработки для образцов, легированных примесями. Обнаруженное возрастание диэлектрической проницаемости обусловлено прыжковым обменом зарядами между дефектами. Проанализировано влияние дефектов разного типа (дивакансии, межузельные дефекты Si–P3 и Si–B2) на диэлектрическую проницаемость и tgδ имплантированного кремния.

Работа выполнена в Лаборатории нейтронной физики им.И.М.Франка ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна, 1996

Zukowski P. et al. E14-96-245

Dielectric Properties of Ion Implanted Silicon Layers

The paper presents results of research into the increase of permittivity resulting from implanting of silicon with ions (N^+, Ne^+, Ar^+) and subjecting it to thermal annealing. Obtained results indicate that the increase of permittivity is caused by jumping charge exchange between defects. The influence of various kinds of defects (divacancies, Si–P3 and Si–B2 interstitials) on permittivity and tgδ of the implanted silicon was analyzed.

The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 1996