94-334

объединенный
институт
ядерных
исследований
дубна

E14-94-334

M.A.Adawi*, A.Yu.Didyk

DAMAGE FORMATION IN SILICON IRRADIATED BY HEAVY IONS WITH ENERGY MORE THAN 1 MeV/a.m.u.

Submitted to Symposium on Advanced in Materials Science,
Cairo, Egypt, 1994

*Nuclear Research Centre, AEA, Cairo, Egypt

1994

1. INTRODUCTION

Ion implantation in semiconductor crystals in the case of high energy, when the specific loss of ionization energy $-(dE/dx)_{inel}$ substantially exceeds the elastic energy loss $-(dE/dx)_{el}$ possesses a series of important properties in comparison with the low energy case. A local heating process takes place in the neighbourhood of the ion track region. This heating process is associated with the high specific ion energy loss. This in turn causes the recombination of primary point defects, interstitials and vacancies. Moreover, the recrystallization of the disordered field even in a very different melted single crystal like diamond[/1/] takes place.

In the present research low and high ohmic samples are used.

2. EXPERIMENTAL METHODS

The irradiation of the samples is carried out by using heavy ions from the U-400 and IC-100 cyclotrons. The ion current density didn't exceed 1 $\mu A/cm^2$ in any cases. The irradiation temperature of the samples was always less than 70^0C.

Investigations of the properties of irradiated samples were carried out by using the optical refraction method, spreading resistance, method of x-ray diffraction, optical microscopy in connection with selective etching. Irradiated samples were prepared and beveled with an oblique angle 4^0 in order to carry out optical reflection measurements. Bevel angles were determined with an accuracy of $\pm 0.01^0$. The measurement of changing in the optical reflection coefficient which takes place as a consequence of radiation damage creation along the polished surface of oblique angle was carried out by using an optical microscope together with the Vidicon detector system. The selected method is described in detail in the work[/2/]. As a measurement of the optical registration of radiation damage the relative change of the reflective index R/R_c is used, where R_c is the reflective index of the non irradiated crystal of silicon.

The profile of spreading resistance in the same samples was obtained by using a double contact electrode system equipped with needle of tungsten carbide (diameter of spike is about 1 μ, the load on the needle is 0.2 grams in suspension). The above-mentioned spreadening resistance profile is received after carrying out one hundred repeated measurements. Every measurement is achieved by using pneumatics touch of two needles, these two needles are parallel to the edge of the polish oblique angle at the same distance along the surface.

In many cases the resistance distribution along the depth of the samples has been determined by taking off the implanted layer and measuring the resistance on the surface. The layer has been excluded by mechanical polishing of a diamond paste. The dimensions of such layer is one μ. The accuracy of polishing in such process was 0.5 μ.

Superficial resistance was measured by using four contact methods by special apparatus IUS-3 (Russia production).

X-ray diffraction measurements have been achieved in a double crystal spectrometer with a parallel situated crystal monochromator and investigated crystal. X-ray irradiation of CuKd1 of copper was used. The crystal monochromator and the samples were cut in the plane [111], and the investigation was carried out in the fourth order reflection (79^0). The interplaner distance was determined by means of angular scattering between the diffraction maximum reflection of x-rays from the attachment and implanted layer. This procedure was achieved by an accuracy of $\pm 5\times10^{-5}$.

3. EXPERIMENTAL RESULTS

First of all let us consider the case of the process which takes part in silicon after implantation of boron ions. These ions are electrically active impurities in the given material.

The depth of the disturbed layer in the case of boron ion implantation with the energy of 13.6 MeV could be evaluated from the spreading resistance curves (see Fig.1) in unheated treated samples. The horizontal part on the curves is due to the limit of the measuring possibility of the installations. In case of irradiating with fluence of 8×10^{13} cm^{-2} the defected layer has the depth of 20 μ, and if the fluence of 8×10^{14} cm^{-2} is used the depth 22.5 μ could be reached. The distribution of implanted boron could be evaluated from the curves which describes the relation between spreading resistance change and the depth, which are received from the investigation of the annealed samples in turn (see fig.2).

The conductivity maximum in the implantation fluence interval of

8×10^{13}-10^{15} cm^{-2} is situated at a depth of 17-18 μ. The calculation of the nuclear and electronic stopping abilities and the profile of the concentration of the implanted boron impurity with using the computer code TRIM-90[3] gives the reduced depth of the maximum ion implantation region (R_p = 16.2 μ). Better coincidence may be noticed if some specific information from the work[4] is used. Concerning the quantity ΔR_p, which characterizes ion dopes the width of the layer, which is doped by ions at the distribution half height. The calculations give the value ΔR_p = 0.51 μ. This value is essentially lower than that obtained from experiment. The experimental value of the ion doped layer is 1.1 μ. There is also a marked difference between the experimental results and those which are predicted from the theoretical formulae. The theory predicts an asymmetric profile which is due to high concentration wing in the direction of the surface. This wing is produced as a result of boron light atoms back scattering on the atoms of silicon. In the experimental profile more intensive wings are noticed at the side of big depth. Such disagreement between theoretical and experimental data may be explained by probable channeling of the part of boron ions which are captured in a channel after ion stopping at non-high energies[5] in turn.

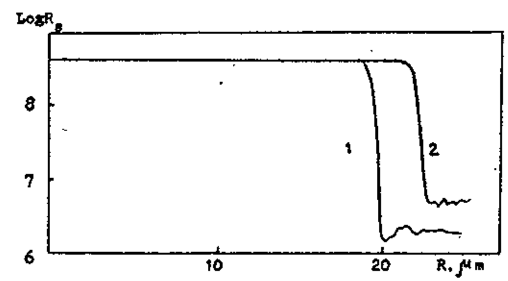

Fig.1. The distribution of the spreading resistance in silicon after implantation of boron ions with energy of 13.6 MeV. The curves 1 and 2 correspond to the fluences of 8×10^{13} cm^{-2} and 8×10^{14} cm^{-2}.

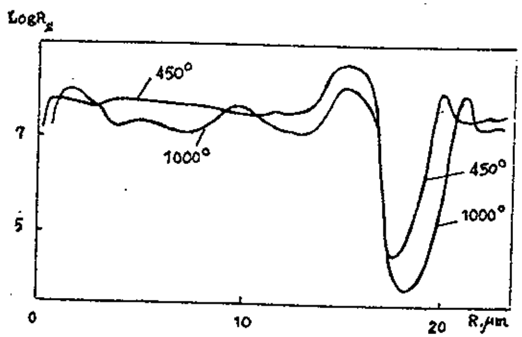

Fig. 2. The distribution of the spreading resistance in 13.6 MeV boron implanted silicon . The irradiation fluence is $8\times10^{13}cm^{-2}$ and the samples are annealed at 450^0 and 1000^0.

The beginning increasing distribution of amorphic phase along the depth of the irradiated layer could be given by means of optical reflection measurements (see fig.3(2)). It is obvious that, the maximum of the amorphic phase distribution and consequently the maximum of the nuclear stopping of the boron ions are situated at the depth of 18 μ. This quantity is in good agreement with the maximum obtained from the experimental curves which represents the implanted boron distribution. The shape of the optical reflection profile curve qualitatively coincides with theoretically calculated quantity $-(dE/dx)_{el}$, i.e. it has more spreading wing in the direction of the surface, however, the experimental value of the peak width of 1.8 μ is comparatively larger, than calculated theoretically one (0.8 μ).

In case of argon ion irradiation (energy of ions 46,3 MeV) the depth of the damage layer from the measurements of spreading resistivity is less for a fluence of 5×10^{14} cm^{-2} than 1×10^{13} cm^{-2} and has the average value of 16 μ. The space distribution of the amorphous centers is obtained from the measurements of optical reflection distribution with the depth presented in fig.3(1). As shown in fig.4 the defect formation maximum is situated at the depth of 12.6 μ. The maximum depth of introducing amorphous phase is 14 μ.

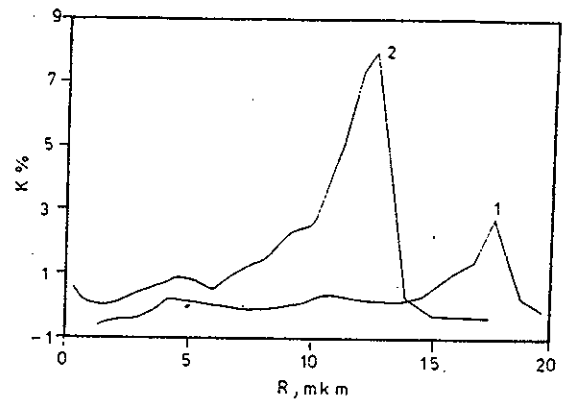

Fig. 3. The reflective index relative change distribution $\Delta R/R_c$ at the wavelength of 650 nm in case of 13.6 MeV boron ions (the fluence is Ft= 8×10^{14} cm^{-2}) - curve 1 and for the 46.3 MeV argon ions - curve 2 (the fluence is Ft = 5×10^{14} cm^{-2}) implantation in silicon.

The comparison between the profiles of the electrically active defect distribution and the optical reflection intensity shows deep penetrability of point defects which change the electrical parameters of the sample in turn. The half height width defect distribution profile which is obtained by means of optical reflection is equal to ΔR_p=2.2 μ, which is much larger than the calculated profile width of the distribution of the elastic loss of argon ions , this value is ΔR_p = 0.95 μ (TRIM-90). The calculated and experimental profiles (see fig.3) coincides with each other qualitatively, i.e. there is a characteristic "tail" in the direction of the surface and a sudden failure in the direction of large depths. There is also a good agreement between the calculated and measured quantities of the average projective range.

The x-ray diffraction method was used for the investigation of the lattice constant change character Δa in the implanted layers as a function of ion fluence and of the depth in irradiated layer. The variation of lattice constant was determined by means of the angular distance between the maximum reflection from the implanted layer and the backing.

In fig.4 the changes of the lattice interval versus fluence in silicon layers implanted by argon is presented. The curves 1 and 3, mainly, refer to the surface layer of the defects of 4-5 μm thickness and the curve 2 reflects the change of the lattice interval due to defects localized at the depth more than 10.5 μm. As seen from the figure, the accumulation of damage is of a sublinear character in the region of argon fluences from 3×10^{14} up to 10^{15} cm^{-2}, Δa is of order $(Ft)^{0.5}$. On further increasing the fluence the parameter Δa tends to saturation. The sublinear character of accumulation of disturbances is associated with annihilation of newly originating moving defects with earlier stable defects. One should note that at usual implantation energies (tens and hundreds keV) at room temperatures the sublinear defect accumulation is typical only for light ions producing, mainly, simple isolated defects but not their clasters. In this connection it makes sense to consider that in case of high-energy argon implantation simple defects are also mainly formed.

Radiation defects distribution of the silicon layer implanted by argon in depth is presented in Fig.5 by the curves 1 and 2 for ion fluences 3×10^{14} and 3×10^{15} ions/cm^2, respectively. The curves 1 and 2 are obtained by measuring the lattice period at the layered controlled etching of sample layers. Defect concentration is calculated by measured value Δa in the layer with reference to backing taking into account that the value of atoms' shift to the region of prevailing damage is 0.2 A. The curve 3 of theoretical distribution of stable disturbances in depth is plotted from the curve of energy losses for elastic interactions. This curve is calculated by the Monte-Carlo method on the assumption that stable complexes form 5%

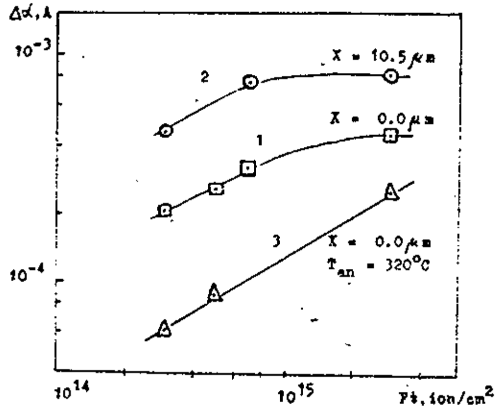

Fig.4. The fluence dependences of lattice constant changes in Si, irradiated by argon ions with energy 46.3 MeV. The curve 3 corresponds to the silicon samples annealed at 320°C.

of all formed vacancies. Experimental values of disturbances in the surface silicon layer irradiated by argon ions of 3×10^{14} cm^{-2} fluence are close the theoretical ones. With increasing the depth damage concentration increases but more slower than the calculated one. This progressing nonconformity of experimental and theoretical values with the depth can be explained by annihilation processes. And really, annihilation processes increase with increasing the concentration of stable defects, i.e. with the depth. However, the vicinity of experimental and theoretical values near surface cannot be the evidence that the main mechanism of the defect formation is the energy loss of high-energy ion for elastic interactions. As the defect accumulation is of a sublinear character, then at fluence of 3×10^{15} cm^{-2} the experimental values (the curve 2) are much more low than the calculated ones (for fluence of argon ion 3×10^{15} cm^{-2} the calculated curve 3 has to be multiplied by the factor 10). For fluences lower than 3×10^{14} cm^{-2}, in view of the same reasons, the experimental values should be higher than the theoretical ones, i.e. one should admit the existence of additional mechanism of defect formation. High values of ionizing energy losses allow one to suppose that the additional defect formation for argon ions with the energy of 46.3 MeV is due to the Coulomb repulsion of ionized lattice atoms- the Coulomb explosion.

The restoration of the period of silicon lattice implanted by high-energy ions during the isochronous annealing process is shown in fig.6 (the curves 1 and 2). For comparison the curve of isochronous silicon annealing implanted by silicon ions with energy of 200 keV is given. The restoration period of the lattice proceeds by two stages: the first -100-300°C, the second -400-600°C. Intrinsic damage in silicon irradiated by silicon ions of keV energies are annealed in a similar way. The first stage of restoration period of the lattice is due mainly to annealing of di-vacancies. At the second stage multivacancies complexes formed in places of vacancy accumulation as a result of defect rearrangement under heat treatment are annealed. It is also known, that stable interstitial complexes of two types annealing at 120 -140°C and 500-600°C, respectively, are formed in silicon implantation in comparable concentrations with vacancy defects. However, these defects do not manifest themselves in changing the period of silicon lattice. Taking account of sublinear accumulation of radiation defects that testifies partial annihilation of newly formed defects the question arises of what defects mainly dissappear in the region of accumulation during implantation isolated or concentrated ones. One can find the answer if to obtain the fluence dependence of changing the period of the lattice during defect accumulation formation.

In fig. 4 (the curve 3) changing the period of the lattice versus argon ion fluence due to defects which are responsible for the second stage of annealing is shown. As seen, their concentration increases within the fluence dependence:

$$N_{def} = k\ (Ft)^{0.6}$$

at all fluences investigated from 3×10^{14} up to 3×10^{15} cm^{-2}. k is the coefficient of proportionality, F is the intensity of ion beam and t is the time of accumulation of the fluence. Here, dependence yield for saturation is not observed. Therefore, mainly the isolated defects participate in annihilation.

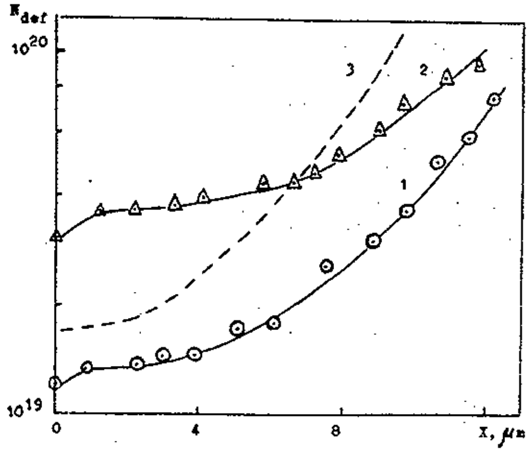

Fig. 5. Distribution of radiation defects in depth of silicon layer (Si doping by boron - SDB-10 [111]) implanted by ^{40}Ar (46.3 MeV). o - Ft = 3×10^{14} cm^{-2}, Δ - Ft = 3×10^{15} cm^{-2}, dotted curve - the calculation.

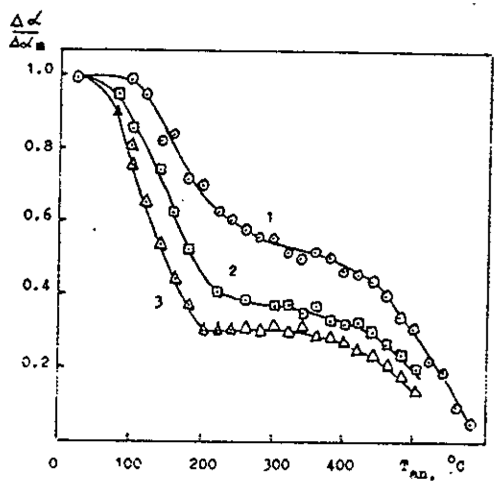

Fig. 6. The curve of restoration period of the lattice at the isohronous silicon annealing SDB-10 [111] implanted by argon ions with the energy 46.3 MeV, o-Ft=3×10^{15} cm^{-2}, □-Ft=3×10^{14} cm^{-2} and Δ - by silicon ions with the energy of 200 keV.

The distribution of radiation defects as a function of the depth of the irradiated layers was determined by using X-ray diffraction, the behavior of the accumulation and annealing near the surface region of silicon crystal implanted at room temperature by neon and argon ions with energy 1 MeV/amu and also kripton ions with energy of 210 MeV. The experimental results are compared with the results obtained from a standard computer code TRIM-90. In fig. 7 the changes of the lattice

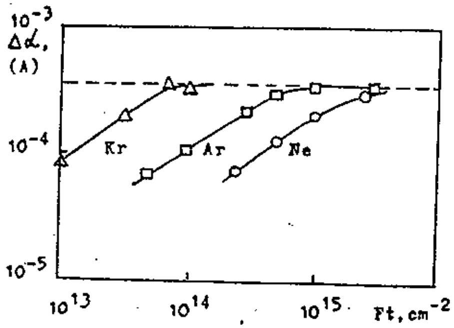

Fig. 7. The dependence of the lattice parameter changes in silicon implanted by ^{22}Ne, ^{40}Ar and ^{84}Kr ions with 26.7 MeV, 46.3 MeV, 210 MeV energies respectively on the fluence.

parameters of the silicon are presented after the irradiation by ^{84}Kr, ^{40}Ar and ^{22}Ne.

The concentration of the introduced damage is higher for the ions with large masses. The behavior of the damage accumulation in the range near the surface is the same for all ions. The concentration of the stable defects grows with the increase of the fluence according to the relation:

$$N_{def}= k\ (Ft)^{0.7}.$$

In this case for some defined for each ion fluences, the velocity of damage formation strongly decreases and the curves characterizing the change of the lattice constant reach saturation. The recalculation of the threshold fluences (which corresponds to the saturation in the dose dependence) to the dose dependence shows that it is impossible to explain the noticed defect concentration on account of elastic losses of energy only. The sudden decrease of the damage formation velocity with the irradiation fluence growth ensures the tolerance of an additional annihilation mechanism of elementary defects. The reason is that the mean distance between the close tracks of ions decreases by increasing the fluence. In case of increasing the ion masses, it could be considered that the track diameter increases, i.e. the overlap of the defects from close tracks for large mass of ions takes places at comparatively low fluences. This effect increases the recombination of point defects between themselves from the close tracks. This leads to the decrease of their accumulation velocity. The value of the fluence threshold $(Ft)_{thr}$ enables to evaluate approximately the track diameter of the ion from the expression:

$$r_o= (Ft)_{thr}^{-1/2}.$$

Then these radii are equal to 3.2 A, 5.0 A and 13.4 A for the Ne, Ar and Kr ions, respectively.

CONCLUSION

On the basis of the obtained results the following could be concluded:

- High energy ions could be used as a powerful tool for studying radiation damage in semiconductor single crystals. In this case it is possible to obtain the high damage velocity formation with large ion free range, which enables to use the classical methods of semiconductor technology.
- The implication of heavy ions reveals them as active impurities which change the type of conductivity in turn, permits the possibility of forming an electrically conducting layer at the far depth of semiconductor materials and multilayer structure which remain stable during the heat treatment.

REFERENCES

1. Didyk A.Yu., Zaitsev A.M., Caramian C.A. Rapid communication JINR, N 4[37]-89, Dubna, 1989, p.44-49.
2. Heidemann K.F. Phyl.Mag. 1981, B44, 465 p.
3. Ziegler J.F., Biersack J.P., Littmark U. The Stopping and Range of Ions in Solids. Pergamon Press, 1985, v.1, 321 p.
4. Northclife L.S., Schilling R.F. Range and Stopping Power Tables for Heavy Ions. In: Nuclear Data Tables. Acad.Press., A7, 233 p.
5. Zaitsev A.M., Fedotov S.A., Melnikov A.A., Komarov F.F., Fahrner W.R., Varichenko V.S. and te Kaat E.H. Nucl. Inst. and Meth. in Phys. Res. B82, 1993, p.421-430.

Received by Publishing Department
on August 17, 1994.