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STUDY OF THE DISTRIBUTION PROFILE OF MECHANISMS GLAND WITH IMPLANTATION METHOD

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Annotations:

In this article on ions with the (110) orientation were implanted into the silicon single crystal. Using the RBS (Rutherford backscattering) method, in combination with channeling, the distribution profiles of the embedded impurity were studied; in addition, the distribution profiles of radiation defects located in the crystal lattice were studied. The simulation results in the TRIM (to'liq nomi kerak) program are compared with the experimental results. It is shown that, at an energy of 4.6 keV / nucleon, a coincidence of the average projective ranges is observed, and when the energy falls to 1.6 keV / nucleon, a difference of 35% is observed. The dose dependence is not taken into account correctly at an energy of 1.6–4.6 keV / nucleon.

Introduction

To create and further modify structures of a solid nature, the method of ion implantation is mainly used. At the present stage of development of the electronic component base, a high degree of integration can be noted, requiring the creation of semiconductor structures with sizes of the order of tens and units of nanometers, and this corresponds to the implantation energy in the range of tens and hundreds of keV [1-4]. Elements of microcircuits of a key nature are designed and created; in these microcircuits, the active element is implemented by several or even one atom. Prototypes of monatomic one-electron devices were demonstrated: quantum bit [5-7], quantum logic gate [8], devices for quantum metrology [9,10], ultrasensitive charge sensors for biological applications [11]. The performance characteristics of the chip will help determine the simulation accuracy of the distribution that is embedded in the impurity in depth.

Although the theory of interaction of accelerated charged particles with solids and an extensive experimental database for high energies are well developed, those programs that simulate the penetration of an impurity into a target usually give a result that differs from the result observed in the experiment by tens of percent [12]. When heavy ions of gold, iron and xenon were implanted [13-15], whose energy was 50-70 keV, into silicon oxide and into a single crystal, between the average projective paths determined in the experiment and calculated using the SRIM-2013(to'liq nomi) program (TRIM) [16,17], we found a discrepancy that ranged from 40 to 50%, and 14% for an energy of 300 keV. And when heavy ions with energies from 10 to 300 keV are implanted into carbon, the experimental values of the average projective ranges calculated in TRIM turned out to be 20-40% lower [12]. Such a difference in the range of 11-20% was found when xenon ions with energies of 20-

300 keV were implanted into silicon carbide. In [19], as a result of the implantation of xenon ions into a silicon single crystal with energies ranging from 200 to 600 keV, the difference between the ranges calculated in TRIM and the measured average projective ranges was only 3–8%. In [20], the successive implantation of 80 keV Ga + and 40 keV N + ions into silicon yielded a result in which the experimental projective ranges coincide with the result of the TRIM program calculation. In some works, the results of calculations using the TRIM program are taken as a standard and are used to interpret the experimental results, despite the indicated discrepancies [21]. Thus, at low and medium energies for heavy ions, there is a significant difference between the calculated and experimental distributions of implanted particles, especially at implantation energies of several keV per nucleon.

In this work, we present the experimental results on the study of the distribution profiles of iron ions implanted with energies of 1.6 and 4.6 keV / nucleon into a silicon single crystal and the resulting defects in the crystal structure of the target. The experimental data are compared with the calculations obtained using the TRIM program. Iron ions for silicon modification were chosen because iron has promising magnetic and optical properties [15, 22, 23].

Experimental technique

Experiments on the implantation of iron ions (Fe +) into single-crystal silicon Si (110) were carried out by the Laboratory of Ion-Beam Nanotechnologies of Moscow State University at beam energies of 90 and 250 keV on the basis of the HVEE-500 heavy ion accelerator complex [24].

Due to the fact that the crystal structure of bulk semiconductor materials becomes completely disordered under the influence of ion irradiation at ion doses of 1016 cm-2 [25]. TRIM considers the target material to be completely amorphous, so to minimize the effect of the target structure ordering on the impurity distribution profile, an ion dose of 1016 cm-2 was chosen. Due to the ion beam current density, it was 80 nA / cm2, which excluded heating of the sample during irradiation. Irradiation was carried out at an angle of 7 ° relative to the normal to the sample surface to eliminate channeling along the main crystallographic axes. The uniformity of irradiation was ensured by scanning the sample with a beam in two mutually perpendicular directions. The Faraday cylinders were used to determine the ion current density, which are located in the experimental chamber. All this determined the accuracy of dose collection in combination with diaphragms, which allow suppressing secondary electron emission. The experiments were carried out at room temperature and a residual pressure of 5x10-6 mbar.

Using the Rutherford backscattering (RBS) technique in combination with channeling on the HVEE AN-2500 accelerator, the distribution profile of the embedded impurity and the degree of destruction of the crystal structure of silicon before and after implantation were studied. The energy of the analyzing helium ion beam (He +) was 1.8 MeV at a scattering angle of 165 ° relative to the direction of beam propagation. The samples were investigated in two modes: parallel to the crystallographic axis with the incident beam (110) and in the direction that does not contain open channels. The (110) direction in the crystal was determined by measuring the yield of backscattered ions when the position of the sample was changed relative to the beam. The sample was installed in such a way that the normal to the sample surface and the direction of beam propagation differed from each other by a small angle, ~ (2-4) °. After that, a certain amount of analyzing particles was directed to the sample and the signal from the detector was recorded. The sample on a goniometric system was deflected by a small angle, ~ (0.1-0.2) °, and the process of irradiation was again carried out with a given dose and registration of backscattered particles. The deflection of the sample through small angles with subsequent irradiation was carried out until a characteristic curve was obtained for the dependence of the yield of backscattered particles on the angle between the normal to the sample surface and the direction of beam propagation. Scanning was carried out in two mutually perpendicular planes. The propagation of the beam along the main crystallographic axis corresponds to the position of the sample in which the largest minimum of the yield of backscattered particles is observed (110).

The TRIM program, with the help of which the calculation was carried out, makes it possible to calculate the distribution profiles of embedded particles and the distribution profiles of defects.

In this work, we present the experimental results on the study of the distribution profiles of iron ions implanted with energies of 1.6 and 4.6 keV / nucleon into a silicon single crystal and the resulting defects in the crystal structure of the target. The experimental data are compared with the calculations obtained using the TRIM program. Iron ions for silicon modification were chosen because iron has promising magnetic and optical properties [15, 22, 23].

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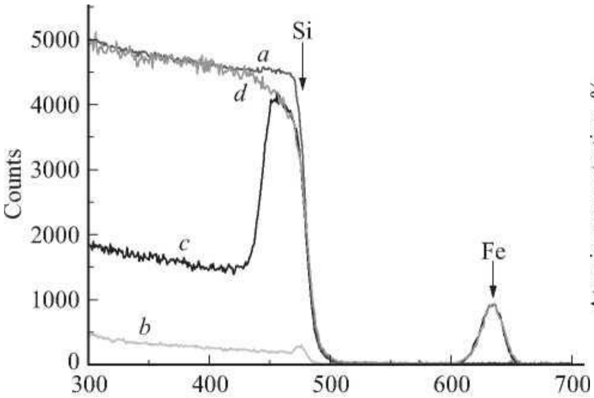

Fig. 1.

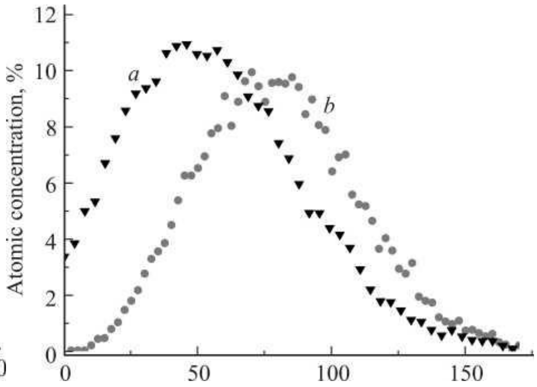

fig. 2.

Figure: 1. Energy spectra of backscattered He + ions with an energy of 1.8 MeV for a scattering angle of 165 ° after implantation of Fe + ions with an energy of 90 keV. Spectra of the original structure: a - in the direction that does not contain open channels; b - in the direction of channeling. Spectra after implantation: c - in the direction of channeling; d - in the direction that does not contain open channels.

Figure: 2. Profile of the depth distribution of implanted Fe + ions with an energy of 90 keV: a - experimental data; b - modeling using the TRIM program.

When a single crystal of silicon is irradiated with iron ions with an energy of 90 keV, an additional peak appeared in the RBS spectra in the high-energy part of the range (curves c, d). This spectrum fits backscattered helium ions from iron. And iron, in turn, penetrated into the size of silicon when the target was irradiated. There is no dip in the spectrum recorded when He + ions are incident in the direction. In this dip, there are no open channels (curve c), in the vicinity of channels 450-500 corresponding to surface layers of silicon, in contrast to the similar range for the initial structure. From this, it can be concluded that, in the area under consideration, the crystal structure in the surface covers is completely broken under the action of irradiation (curve c coincides with curve d). Note that the RBS ranges from the initial structure and after ion irradiation (curves a and d), acquired in the direction that does not have open channels, do not coincide in the region of channels 435–475, which indicates that silicon atoms are replaced by an implanted impurity.

In fig. 2 shows a section of the distribution of implanted iron ions with an implantation energy of 90 keV and a dose of 1016 cm-2 on an enlarged scale (curve a). The transition from energy channels to depth was carried out due to the known values of characteristic costs [26]. This surface contains impurity atoms at a concentration of 3%. The distribution has a maximum at a distance of 50 nm from the plane and a width at half maximum of 80 nm.

The calculation performed in the TRIM program (curve b) gives an invariant arrangement with an average projective range of 77 nm and a width at half maximum of 75 nm. With all this arrangement of implanted atoms, it starts at a depth of about 10 nm from the surface. It should be noted that, according to the RBS ranges, the substitution of the target atoms by the introduced impurity is observed. But TRIM does not take into account the recombination of interstitial atoms with vacancies and the modification of the target composition during implantation. The assessment of taking into account the effect of implanted ions was carried out as follows: iron ions were implanted into the target, which consists of 93% silicon and 7% iron. In this case, the average projective range was 70 nm, and the distribution became narrow (the width at half maximum was 54 nm). Consequently, taking into account the surface modification gives the discrepancy between the mean projective ranges by 6% less than if modeling the process of iron implantation into pure silicon.

It should also be noted that the calculation gives a 25% lower concentration of the incorporated impurity. In work [15], in which a silicon single crystal was implanted with iron ions with an energy of 50 keV and a dose of 2, 16x1017 cm-2, on the contrary, the calculation of the concentration using TRIM gives such values that exceed the experimental data by more than 2 times.

In the next experiment, iron ions were implanted with an energy of 250 keV and a dose of 1016 cm – 2 (Fig. 3). For comparison, the RBS spectrum from the original substrate in the direction that does not contain open channels is shown (curve a). It can be seen that after irradiation there is a regression in the region of channels 400-500 (curve b). The decrease in the silicon concentration in the near-surface cover most likely occurred as a result of the replacement of silicon atoms by intercalated iron ions. In fig. 1, complete disordering occurs after implantation of Fe + with an energy of 90 keV. In contrast, after implantation of ions with an energy of 250 keV, the curves b and c do not coincide. In this case, complete disordering did not occur in the near-surface covers of a silicon single crystal to the path depth of Fe + ions.

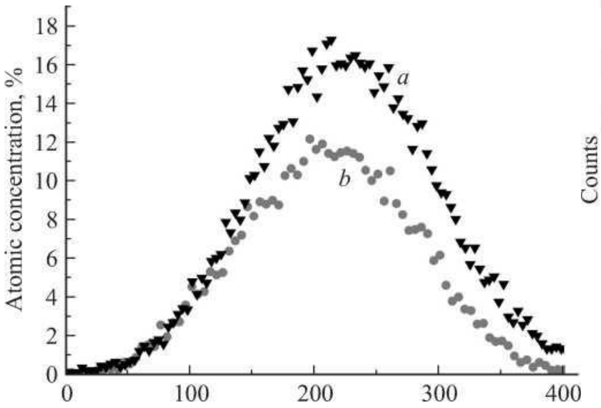

Fig. 3.

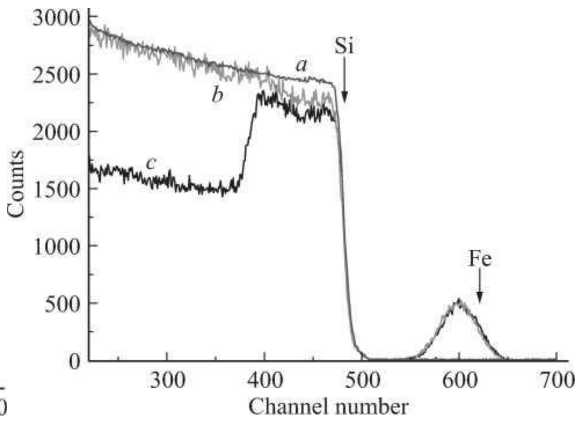

Fig. 4.

Figure: 3. Energy spectra of backscattered He + ions with an energy of 1.8 MeV for a scattering angle of 165 ° after implantation of Fe + ions with an energy of 250 keV. The spectrum of the original structure: a - in the direction containing no open channels. Spectra after implantation: b- in the direction that does not contain open channels; c- in the direction of channeling.

Figure: 4. Profile of the depth distribution of implanted Fe + ions with an energy of 250 keV: a - experimental data; b- simulation using the TRIM program.

The distribution profile of Fe + ions subjected to implantation is shown in Fig. 4 on an enlarged scale (curve a).

The distribution maximum is located at a distance of 220 nm from the surface. According to the TRIM program (curve b), the average projective range of Fe + with an energy of 250 keV in a silicon matrix is 210 nm. The distributions are symmetrical. The widths of the experimental and calculated distributions at half-height were 170 nm. For this energy, we see good agreement between the experimental data and the simulated data. However, a calculation using the TRIM program gives a 30% underestimated concentration of the incorporated impurity.

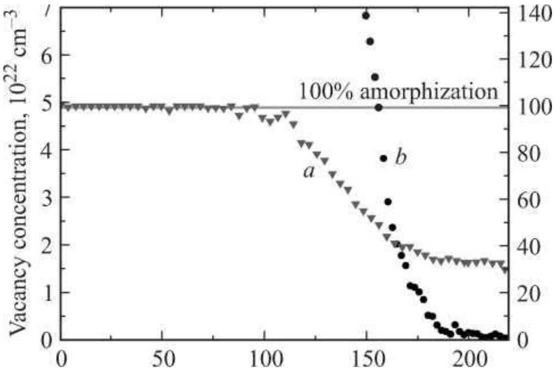

Fig. 5.

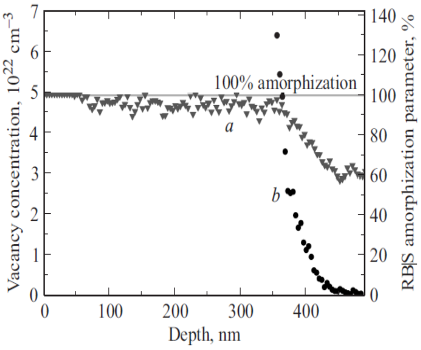

Fig. 6.

Figure: 5. Distribution profile of defects formed after irradiation with Fe + ions with an energy of 90 keV: a - experimental data; b- simulation using the TRIM program.

Figure: 6. Distribution profile of defects formed after irradiation with Fe + ions with an energy of 90 keV: a - experimental data; b- simulation using the TRIM program.

A comparison of the distribution of defects that were determined experimentally (curve a) with the profile of defects calculated by TRIM (curve b) for a beam energy of 90 keV is shown in Fig. 5. The ROP amorphization parameter shows the ratio of the spectral signals taken in the channeling direction and in the direction not containing open channels. When compared with theoretical calculations, the authors considered a silicon single crystal to be completely disordered when the number of displacements is equal to the number of atoms in the layer, i.e., the completely disordered region in the experimental distribution of defects corresponds to a vacancy concentration of 4.9x1022 cm-3 of the theoretical distribution (shown by the solid line). According to theoretical calculations, this amount of displacement is observed at a depth of 155 nm. However, the experimental data show that amorphization is observed only to a depth of 110 nm, and then the degree of disordering drops to 35% at a depth of 180 nm from the surface. The absence of a drop in the yield of backscattered particles to the level of the initial structure in the channeling mode is explained by the dechanneling of the helium ion beam as it passes deep into the crystal through the region destroyed by ion irradiation.

In fig. 6 shows a comparison of the defect distribution profile determined experimentally (curve a) with the defect profile calculated by TRIM (curve b) for an implanted ion beam energy of 250 keV. According to the experimental curve, amorphization occurred only at a depth of up to 54 nm, and up to a depth of 360 nm, the average ROP disorder was 95%. According to calculations, amorphization occurs to a depth of 365 nm. In addition, it can be seen that, for the indicated experimental parameters, the formation of defects deeper than 450 nm does not occur. However, according to experimental data, at a depth of 450 nm, the ROP amorphization parameter is 60%. In this case, in contrast to Fig. 5, there are more de-channeled particles, since the layer modified by ion irradiation is thicker.

Conclusion

The distribution profiles of iron implanted in silicon are studied by the Rutherford backscattering method in combination with channeling. Under irradiation with an energy of 90 keV, the difference between the experimental and calculated average projective ranges is 35%. With an increase in the implantation energy up to 250 keV, the distribution profiles of embedded particles obtained with the help of ROP and TRIM are in good agreement. It was found that with the implantation parameters used, TRIM simulation gives an underestimated by 25-30% of the concentration of the implanted impurity in relation to the experimental data.

An analysis of the defects formed at an energy of 1.6 keV / nucleon shows that TRIM gives an overestimated estimate by 30%. According to the experimental data, with an increase in energy to 4.6 keV / nucleon, complete disordering of the crystal structure of silicon to the depth of penetration of iron ions does not occur. However, the calculation with the indicated implantation parameters in the TRIM program shows the formation of a significantly larger number of vacancies.

Further investigation of the depth distribution profiles of the embedded impurity and radiation defects will make it possible to both solve a number of problems in the applied direction and obtain additional information on the fundamental nature of the interaction of accelerated charged particles in matter.

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