RELATION BETWEEN AMORPHIZATION AND THE FORMATION OF POINT DEFECTS DURING ION BOMBARDMENT OF GERMANIUM AND SILICON

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RELATION BETWEEN AMORPHIZATION AND THE FORMATION OF POINT DEFECTS DURING ION BOMBARDMENT OF GERMANIUM AND SILICON

(Presented by Academician N. V. Belov, 21 X 1969)

It is known that, when germanium and silicon are bombarded with ions of medium energies, a transition of the near-surface layers to an amorphous state is observed. This phenomenon has been investigated by electron microscopy and electron diffraction ($^{1-6}$), and also by the Rutherford scattering method using high-energy ion beams (^{7,8}). On the basis of the data of ($^{3-6}$) it may be concluded that the most probable mechanism of amorphization is the accumulation of radiation defects. At a certain concentration of the latter the crystalline state becomes unstable, and disordering of the structure occurs.

However, the data available in the literature do not make it possible to draw definite conclusions about the relation between the parameters characterizing amorphization (critical amorphization doses, thicknesses of amorphous layers, stability of the amorphous state upon annealing) and the parameters characterizing defect formation under ion bombardment (relative concentration and distribution of point radiation defects under different irradiation conditions). Establishing such a relation would not only provide an additional argument in favor of the proposed mechanism of amorphization, but would also help to explain its regularities, as well as to verify theoretical calculations of defect formation (^{9}). In the present work, the results are given of several experiments indicating that such a relation does indeed exist.

1. In order to determine what influence the species of ions has on the degree of short-range order of amorphous germanium, the structures of amorphized Ge films irradiated (at the same dose of 1000 μC/cm^2) with B$^+$, N$^+$, and Ar$^+$ ions were deciphered by the method of Fourier analysis*.

The degree of short-range order is characterized by the sharpness of the maxima of the radial distribution curve of atomic density. As a measure of order we take the ratio of the height of the maximum h to the width w at zero ordinate. The following values of h/w are obtained for the first two coordination spheres:

Figure 3: Electron diffraction patterns of a Si surface irradiated with B+ ions after removal of layers of various thicknesses.

Figure 1: Figure 3: Electron diffraction patterns of a Si surface irradiated with B+ ions after removal of layers of various thicknesses.

	B^+	N^+	Ar^+
1st coordination sphere	14.7	12.1	7.0
2nd coordination sphere	22.0	21.2	17.9

As can be seen, the degree of short-range order decreases with increasing ion mass. This is due to the fact that, during the rearrangement of atoms occurring in the amorphized layer as a result of the entry into it of accelerated ions, the degree of order must depend on the concentration of broken bonds (or, equivalently, radiation defects) in the cascades of atomic displacements developing as the ions are slowed down. The latter, in turn, increases with increasing ion mass ([9]).

* Data for a dose of 1000 μC/cm^2 were given in ([3]).

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Fig. 3. Electron diffraction patterns of the Si surface irradiated with B+ ions after removal of layers of various thicknesses (dose 1000 μC/cm^2, energy 50 keV). Layer thickness (Å): 1 –400; 2 –800; 3 –1200; 4 –1600; 5 –2000; 6 –2400; 7 –2800; 8 –3200.

2. Figure 1 presents the dependence of the doses D_{am} at which amorphization of Ge and Si occurs under bombardment with B^+ and P^+ ions of various energies, on the concentration of point radiation defects (vacancies) at the surface, n_0, produced per 1 ion/cm^2. The values of n_0 were calculated by the Monte Carlo method.*

It is seen that, with a single exception (bombardment of Si with B^+ ions), the indicated dependence falls on one curve; moreover, over a fairly wide range D_{am} is inversely proportional to n_0. This indicates that amorphization of Ge and Si occurs after the accumulation of a definite concentration of defects, to a certain extent independent of the irradiation conditions. The slower decrease of D_{am} at large n_0 can be explained by enhanced recombination of defects at high densities of the latter in displacement cascades. The departure from the general regularity of the point corresponding to the pair B^+–Si is possibly connected with the fact that boron ions with $E \simeq 50$ keV undergo weakly screened Coulomb collisions, in which the energy transfers to target atoms are small. In this case close vacancy-interstitial-atom pairs are formed, which readily recombine with one another.

Fig. 1. Dependence of the amorphization doses D_{am} of Ge and Si on the concentration n_0 of vacancies at the surface, produced per 1 ion/cm^2. 1–B^+

Figure 1

Figure 2: Figure 1

Figure 2

Figure 3: Figure 2

–Ge; 2–P^+–Ge; 3–B^+–Si; 4–P^+–Si. The numbers next to the experimental points denote the ion energy (keV).

3. By successive removal of thin layers from the irradiated silicon surface and recording reflection electron-diffraction patterns, the thicknesses of amorphous layers h_{am} were measured at various phosphorus-ion energies (Fig. 2). The layers were removed by anodic oxidation followed by dissolution of the oxide films in hydrofluoric acid. The experimental points fit well on the curve corresponding to the calculated penetration depth of radiation defects (^{9}). (The best agreement is obtained when the depth is taken as the abscissa of the point at which the defect concentration is 0.2 of the maximum for the given energy.) An analogous result was also obtained for boron ions.

Fig. 2. Thicknesses of amorphous layers h_{am} in Si as a function of the energy E (dose 300 μC/cm^2). The curve corresponds to the depths at which the vacancy concentration is 0.2 of the maximum for the given energy.

In accordance with the bell-shaped form of the distribution of radiation defects obtained by calculation, it should be expected that at irradiation doses close to D_{am} the amorphous layer lies at some distance from the surface. Figure 3, which gives electron-diffraction patterns of a Si surface irradiated with boron ions after removal of layers of different thickness, confirms this assumption (see Fig. 3 in the insert facing p. 315).

4. Investigation of annealing of amorphized layers of Ge and Si showed that crystallization of Ge occurs at 400-500°, and of Si at 600-700° (time–

* In the calculation the displacement threshold E_d was taken equal to 30 eV.

annealing time $t = 0.5$ h). This agrees with the data reported in the literature (^{1,4,5,8}). The crystallization temperature varies somewhat depending on the type of ion–increasing by $\sim 50°$ for the heavier Ar$^+$ ions compared with N$^+$ or B$^+$ ions. The latter is connected with the tendency noted above toward a decrease in the degree of ordering with increasing ion mass.

Thus, the principal regularities of amorphization under ion bombardment can be explained within the framework of ideas concerning the formation of point defects, without invoking the hypothesis of thermal spikes (^{1}). The only weighty argument in favor of this hypothesis is the appearance of individual amorphous inclusions preceding the formation of a continuous amorphous layer. However, these inclusions may be associated not with thermal spikes, but with coagulation of radiation defects, for example on impurity atoms.

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