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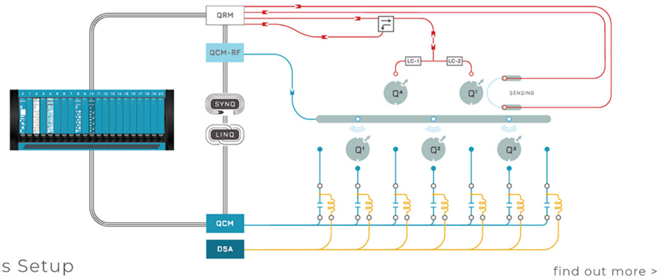

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Energy dependence of amorphizing implant dose in silicon*

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The radiation-induced transformation from crystalline to amorphous silicon was studied using ion implantation. The ion energy was varied from 20 to 180 keV for Li^+, N^+, Ne^+, Ar^+, and Kr^+. The energy dependence of the critical amorphizing dose was determined by electron spin resonance. Comparison of the data with theoretical calculations of the energy density deposited into atomic processes showed good agreement. This energy-dependent agreement gave evidence that energy density is important to the transformation at both low and high implantation temperatures.

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Silicon can be transformed from the crystalline to the amorphous state by ion implantation.[1] It has been proposed[2] that if the energy density implanted by the ions into atomic processes is sufficiently large, then the transformation will occur. At low implantation temperatures, experiments using a variety of ion masses[2] have shown that the implanted volume becomes amorphous when the energy deposited into damage exceeds a critical value E_c. However, for amorphization at higher temperatures a substantially greater ion dose is necessary.[2] An important question is then whether this actually indicates a breakdown in the critical-energy-density model at high temperatures. This letter presents an independent verification of the critical-energy-density model at low temperatures by varying ion energy rather than ion mass. In addition, the high-temperature data also suggests that the critical-energy-density model is still important even though substantially higher doses are required for amorphization.

The implantations were performed on our ion accelerator with voltages from 20 to 180 kV. The samples were *n*-type silicon with resistivities exceeding 10 Ω cm. Typically, a series of ten samples was implanted at each energy. Each sample in the series was exposed to a different ion dose. The signal intensity of the amorphous electron spin resonance line at $g = 2.006$ was measured for each sample. Comparison of these intensities permitted determination of the critical (saturation) dose at which the implanted volume becomes continuously amorphous.[3] This critical dose was determined throughout the energy range for a light (Li^+), intermediate (Ar^+), and heavy (Kr^+) ion. The data points are shown in Fig. 1 for implantations into silicon samples at a low temperature (80 °K). This data can be used to test the critical-energy-density model.[2]

If this model is correct, then at the critical dose the energy balance between the average energy density deposited into atomic processes and the critical energy density can be written as

$$D\nu/X_m = E_c, \tag{1}$$

where D is the critical dose (ions/cm²), ν is the energy deposited per ion into atomic processes, and X_m is the depth of the damage (e.g., depth corresponding to 90% damage accumulation). Whether E_c is actually a constant can be tested by comparing the critical dose data with theoretical values for ν/X_m. The solid curves in Fig. 1 are plots of $E_c(\nu/X_m)^{-1}$ for the experimentally determined[2] E_c value of 6×10^{23} eV/cm³ and ν/X_m values extrapolated from Ref. 6. (Extrapolation from Ref. 7 give similar values.)

The calculations for the light ion (Li^+) show a definitely increasing energy dependence as observed. For the intermediate ion (Ar^+), the calculations and data show little change with energy. For the heavy ion (Kr^+), the data show essentially no energy dependence at the higher energies with increased lower energy values. The calculations show a slight increase at lower energy, but not as much as observed. The agreement in absolute value is not as good. It shows no consistent trend with ion mass and can not be improved by adjusting E_c. However, when the complexity of the radiation damage process and the uncertainties in the measurements are considered, the over-all agreement with the simple form of Eq. (1) seems quite reasonable.

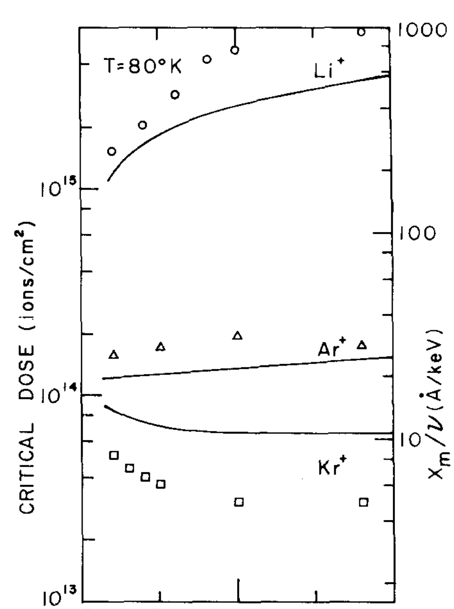

FIG. 1. Critical amorphizing dose for various ion energies at low temperature (80 °K). The data points were obtained for a light ion (Li^+, ○), intermediate ion (Ar^+, △), and heavy ion (Kr^+, □) in silicon. The dose rates (Ref. 4) in the three cases were 1.6, 0.32, and 0.16 μA/cm², respectively. The solid lines are theoretical curves for the same three ions assuming the critical-energy-density model.

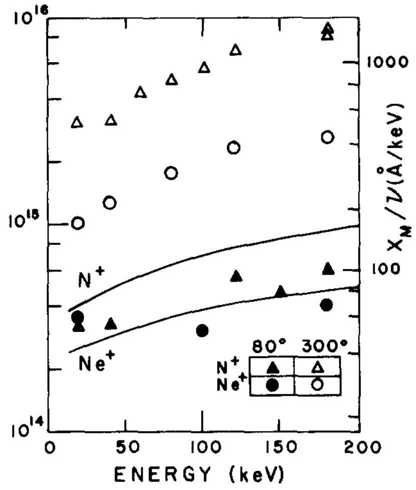

FIG. 2. Critical amorphizing dose for various ion energies at high temperature (300 °K). Similar to Fig. 1 except values are for both N (Δ) and Ne (○) ions at low temperature (filled symbols, 80 °K) and high temperature (hollow symbols, 300 °K) with dose rates (Ref. 4) of 1.6 μA/cm^2 for N$^+$ and 0.8 μA/cm^2 for Ne$^+$.

The energy dependence occurs because a greater fraction of the total ion energy goes into electronic processes as the energy is increased. The important ratio X_m/ν changes only slightly with energy because both the numerator and denominator increase with energy. Of importance for analysis are the small changes in the energy normalized form of the ratio $(X_m/E)/(\nu/E)$. For a light ion, electronic losses increase substantially with energy. In such a case, ν/E decreases substantially more than X_m/E and causes an increasing critical dose as in Fig. 1. For other masses the numerator and denominator both change, but the ratio has only subtle changes. An exception is the case of heavy ions at low energy where disproportionate changes in X_m/E causes a decrease with decreasing energy.

Implantations at both a high (300 °K for light ions) and a low (80 °K) temperature have been performed with both N$^+$ and Ne$^+$. These results are shown in Fig. 2. The solid curves are the theoretical results for the initially deposited energy density and show basic agreement with the low-temperature data as in Fig. 1. Of special interest is the fact that the high-temperature data has the same energy dependence, but essentially an order of magnitude larger critical dose was found. To evaluate whether this actually indicates an order of magnitude breakdown in the critical-energy-density model, a model previously proposed for the temperature dependence of the critical dose should be considered.

In this model[8] the critical dose increases with temperature because the area which becomes amorphous around each ion track decreases with temperature. This decrease of area was attributed to vacancy out-diffusion from the center of the ion track[8–10] where a high vacancy concentration was initially created and necessary for the lower density of amorphous silicon.

From an energy point of view a diffusing vacancy takes its formation energy with it, and thereby reduces the energy density in the heart of the damage track. (There is some evidence to suggest that the damage energy is actually lost when vacancies annihilate with knocked-out silicon atoms on the periphery of the damaged region.[11]) This energy out-diffusion causes a contraction of the critical-energy-density contour about the ion path. This continues until the atomic rearrangements going on in the core of the track stabilize into an amorphous configuration. The area which is no longer within the critical contour must now receive additional deposited energy and hence a greater dose for amorphization. Thus, as before, when vacancy diffusion occurs at the higher implantation temperatures, a greater dose is required.

In summary, additional data has been taken to establish the conditions under which silicon becomes amorphous. This data provided an independent verification of the energy density model. It also shows that the energy dependence of the critical dose is the same for both high and low temperatures, even though the critical dose changed substantially.

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