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Abstract

Monocrystalline silicon has been irradiated by MeV carbon clusters (C_n , $n=1,2,3,4$) with fluences up to $3 \cdot 10^{16}$ C atoms per cm^2 . The produced defect concentration in a depth between 100 and 200 nm below the sample surface has been measured by channeling RBS. For energies above approximately 0.5 MeV per carbon atom the polyatomic particles produce less defects per incident atom than single C ions of the same velocity. This effect increases with energy and cluster size. The largest reduction of the produced defects per atom measured so far is 40% for the C_2 molecule at an energy of 4 MeV per C atom. A possible explanation for the effect is an increase in the defect annealing rate caused by the larger primary point defect concentration and the enhanced deposited energy density along a particle track.

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1. Introduction

In recent years, experiments with polyatomic ion beams have gained considerable interest. In the very low energy regime (eV per atom) cluster beam deposition of thin epitaxial films has been investigated successfully [1]. In the keV per atom regime strong collective effects in surface sputtering and secondary electron emission have been observed [2]. For MeV energies very scarce data on nonlinear effects caused by cluster impacts exist. An enhanced energy loss per incident proton has been measured for H_n -clusters passing through thin foils [3]. Recently a reduction in secondary electron emission per incident atom has been observed with H_n -clusters [4].

At elevated beam energies it is of particular interest to investigate the phenomena induced by the extremely high density of deposited energy produced by multiple simultaneous impacts. For a single particle the maximum energy loss that can be reached e.g. in silicon is 25 MeV per μm of the ion track [5]. In order to obtain this value the heaviest single atoms (e.g. ^{238}U) have to be accelerated to more than a GeV. In the case of polyatomic particles the same energy density can be obtained with a C_{25} cluster with a total energy of only 20 MeV (0.8 MeV per atom). This brings a series of interesting experiments well into the reach of small accelerator laboratories.

In comparison to high energy heavy ion bombardment, cluster irradiation offers some additional advantages for the basic investigation of radiation induced effects in function of the deposited energy density. Since the chemical bonds between the cluster constituents are broken on impact (in the first few atomic layers of the target) the average distance between the fragment tracks increases with depth due to straggling and the Coulomb repulsion between the individual ions (see fig. 1). After a small fraction of a μm the distance between the ions has become large enough to rule out important nonlinear effects in the primary scattering processes (i.e. the distance between the fragments is much larger than the relevant impact parameters of nuclear and electronic scatterings). For example, a 1 MeV C atom produces only approximately 50 atomic displacements per μm of ion track length in Si [10]. Thus, by changing the cluster size at a constant energy per atom, the density of deposited energy can be altered without affecting e.g. the ratio between electronic and nuclear energy loss or the energy and range distribution of δ -electrons and recoil nuclei, as long as the first few nm below the material surface are disregarded.

In the experiments presented here the defect density produced by small carbon clusters (C_n , $n = 1, 2, 3, 4$) in silicon single crystals has been investigated. The energy of the clusters was between 0.2 and 4 MeV per carbon atom. At these energies the energy loss is strongly dominated by electronic stopping. Except for the irradiations at 0.2 MeV per atom the nuclear stopping is less than 1% of the total energy loss. Therefore, the number of defects produced along one ion track is small and the defects are far apart. Thus, it was possible to study the effect of the total deposited energy density on primarily produced defects by varying the cluster size.

2. Experimental Details

Experiments have been performed at the PSI/ETH Tandem accelerator laboratory at ETH-Hönggerberg. The essential details of the irradiation set-up are displayed in fig. 2. The primary beam of negative carbon cluster ions is produced in a Cs-sputter source. The negative ion beam is energy and momentum analysed in a 90° electrostatic deflector followed by a 90° dipole magnet [6] and injected into the 6 MV EN Tandem accelerator. The magnet is able to deflect ions up to a mass of 350 amu at an energy of 40 keV. Typical currents are listed in table 1. At the high energy end of the accelerator an energy to charge state ratio is selected with a 15° electrostatic deflector. The irradiation station is placed at a focal point 1.5 m behind the deflector. Only for charge state +1 beam intensities useful for irradiation purposes have been obtained (table 1). The overall transmission from the ion source to the target is approximately 1 %. It is mostly due to the probability of nondestructive stripping of the clusters in the Ar gas cell at the high voltage terminal of the accelerator. Currents at charge state +2 are orders of magnitude lower. Since fragments from cluster break-up in the stripper have different energies the electrostatic analysis is unambiguous and selects the unbroken clusters. Contamination by monoatomic particles (e.g. ^{48}Ti in the case of $^{12}\text{C}_4$ or ^{60}Ni in the case of $^{12}\text{C}_5$) cannot be ruled out, though. Therefore, several experiments have been performed to estimate the monoatomic contamination of the cluster beams. In a first test, a gold coated carbon foil has been placed after the electrostatic deflector and the produced fragments have been momentum and energy analysed by a magnetic spectrometer followed by a $\Delta E/E$ gas ionisation chamber (fig. 2). In the case of C_5 clusters, ^{12}C ions with the appropriate energy (1/5 of the cluster energy) have been detected in 1 to 5-fold coincidences in the ionisation chamber (corresponding to the number of fragments accepted by the magnetic spectrometer). ^{60}Ni ions were nearly absent (below 1 %) in any possible charge state. In a second test, a silicon surface barrier detector has been placed behind the gold/carbon foil at 45° to the beam. Again, events corresponding to the scattering of ^{12}C ions with the appropriate fraction of the cluster energy have been detected. The signal of monoatomic beam contaminants was below 1 % in all cases. These two tests proved that the clusters pass through the electrostatic deflector and reach the target intact. In a last test, a $3\text{ }\mu\text{g}/\text{cm}^2$ carbon foil followed by a CR-39 nuclear track detector foil (spaced by 1 mm) was irradiated with a very short beam pulse. Groups of cluster fragments could unambiguously be identified on the track detector foil (see fig. 3). The average distance between the fragments in one group was between 10 and $20\text{ }\mu\text{m}$ which is in good agreement with the value estimated by the effects of Coulomb explosion and angular straggling in the carbon foil. Thus, the clusters reach the irradiation station in an intact manner and only break up at the target surface.

Rectangular ($17\times 23\text{ mm}^2$) pieces of (100) and (111) silicon wafers have been irradiated at a tilt angle of 8° off the main axis. On each sample 6 rectangular spots of $3\times 3\text{ mm}^2$ were irradiated. In order to obtain homogeneously irradiated areas the beam was scanned across a collimator placed 10 cm in front of the target with two magnetic steering devices at frequencies of 11 and 19 Hz, respectively.

The target was periodically moved out of the beam in order to measure the beam current in a Faraday cup behind the target. The current density was in all cases below $1\mu\text{A}/\text{cm}^2$. Irradiations have been performed at room temperature. For each cluster irradiation, a single carbon atom irradiation with the same fluence and the corresponding energy per atom was done on the same sample for comparison, in order to rule out the influence of possible differences in the wafer quality. Fluences ranged from $1\cdot 10^{15}$ to $3\cdot 10^{16}$ C atoms per cm^2 and energies from 0.2 to 4.0 MeV per C atom (see table 2).

The produced defect density has been analysed with 2 and 3 MeV ^4He channeling Rutherford backscattering spectrometry (CRBS). The channeling set-up has been described in ref. [7]. The ^4He beam spot was approx. 1 mm^2 at a current of 10 nA. The crystal axis perpendicular to the silicon wafer surface has been aligned to the beam using standard procedures [8]. Aligned energy spectra have been measured at an unirradiated (virgin) spot of the sample and at all the irradiated areas. Since the used goniometer has an xy-stage this was possible without any change to the crystal alignment. For each sample several energy spectra under random orientation have been taken (fig. 4). Values for the minimum yield (χ_{min}) have been obtained by dividing the integrated yield in an energy region corresponding to a depth interval between 100 and 200 nm below the sample surface by the yield of the random spectrum. It has then been assumed that the fraction of Si atoms displaced from lattice sites by the irradiation (n_D) is proportional to the increase of χ_{min} of an irradiated area compared to χ_{min} of a virgin spot. For simplicity the proportionality factor was assumed to be 1:

$$n_D = \chi_{min}(irr) - \chi_{min}(vir)$$

This means that the determined defect concentrations are given in arbitrary units, though it is generally assumed that the incremental χ_{min} is a good approximation for the fraction of displaced atoms [8, 9]. All experimental values for n_D are listed in table 2. The experimental error of n_D is approximately 5% and is due to the counting statistics and charge normalization of the CRBS analysis. Some of the irradiations have been repeated up to three times and no deviations beyond these statistical fluctuations have been found.

3. Results

The range and the defect concentration at the end of range of the ions was the same for single C atoms and clusters at a given energy per C atom. This was expected since the stopping power of single atoms and molecules differs only significantly in the first few nm of the sample [3] and, thus, the total effect on the ion range is not measurable. Therefore, the height and position of the end of range peak has been used at low fluences (10^{15}cm^{-2}), where the stop region is not yet amorphised, to verify that the energy per C atom and the measured fluences agree for single C and C_n irradiations. No significant deviations have been found. In the following, all quoted defect concentrations refer to the above mentioned depth interval between 100 and 200 nm below the sample surface.

For C_4 clusters the evolution of the defect density with the irradiation fluence has been measured and compared to the case of single C atom irradiation at an energy of 0.8 MeV per C atom (fig. 5). The data can be fitted well by a saturation curve of the form

$$n_D = n_o(1 - e^{-\frac{F}{F_o}})$$

where F is the C atom fluence, n_o the saturation defect concentration and F_o the saturation fluence at which $(1 - \frac{1}{e})n_o$ is reached. For single C atoms $n_o = (3.1 \pm 0.1) 10^{-2}$ and $F_o = (2.5 \pm 0.2) 10^{15} \text{ cm}^{-2}$ while in the case of C_4 clusters $n_o = (2.3 \pm 0.1) 10^{-2}$ and $F_o = (2.2 \pm 0.3) 10^{15} \text{ cm}^{-2}$ are obtained. The slope $\frac{n_o}{F_o}$ of this curve at zero fluence represents the defect production cross section. In both cases this cross section is approximately $1 \cdot 10^{-17} \text{ cm}^2$ which compares well with the value obtained with the simple Kinchin-Pease model [10]. This corresponds to the displacement of approximately 50 Si atoms per μm of ion track length.

In fig. 6 measured defect saturation curves for 0.8, 1.5, and 3 MeV single C atoms are compared to 0.8 MeV per atom C_4 irradiation. Obviously, the C_4 clusters have a similar effect on the material like single carbon atoms of approximately twice the energy.

The ratio between the defect concentration produced with clusters to the one of single C atom irradiation has been measured in function of the energy for various cluster sizes at a constant C atom fluence of 10^{16} cm^{-2} (see fig. 7). At this fluence the saturation defect density is almost completely reached so that in principle n_o is measured. The low energy part of the data is perfectly in agreement with similar irradiation experiments done with Te_2 , As_2 , and P_2 molecules on silicon (at a temperature of 35 K) in the energy range of 10 to 60 keV per atom by Thompson and Walker [11].

In fig. 8 the ratio between the saturation defect density produced by clusters and single atoms at an energy of 0.8 MeV per atom is plotted versus the cluster size. In order to get additional information about the cause of the reduction of the saturation defect density with cluster projectiles a cycling experiment has been performed. Samples irradiated with 10^{16} cm^{-2} 0.8 MeV C atoms have been postirradiated with various fluences of 0.8 MeV per atom C_4 clusters. The results (Fig. 9) suggest that the defect density can be cycled between the saturation densities of single C atom and C_4 irradiation.

4. Interpretation

4.1. Primary Defect Production

The above results confirm the known fact [12, 13] that the defect concentration in the surface region of MeV light ion irradiated silicon saturates at a level corresponding to a few percent of atoms displaced from their lattice site. This means that for high enough fluences there exists an equilibrium between the defect creation and the defect recombination (annealing) rate. The observed 'cluster effect' implies that for polyatomic projectiles this equilibrium is shifted in favor of the

recombination rate. The effect becomes more pronounced with increasing cluster size and energy per atom. The largest effect observed so far is a 40% reduction of the saturation defect concentration (fig. 7). Possible explanations of the phenomenon can either base on a decrease of the defect production rate, an increase of the recombination rate or both. If we assume that the electronic stopping does not contribute to the defect creation, all primary defects have to be produced by nuclear scatterings. In order to explain nonlinear effects in the number of atoms displaced by nuclear collisions several possibilities can be discussed. The fragment tracks might be close enough to allow for the 'guiding' of one particle by the other in a way that the fragment in front is clearing the path for the trailing one. Coherent multiple scattering of molecules has indeed been observed and explained by so-called 'wake potentials' [14, 15]. All observations, though, have been made in thin foils of only tens of nm and one would expect the effect to disappear as soon as the lateral distance of the fragment tracks becomes larger than an atomic distance in the material (see fig. 1).

With a displacement energy of 20 eV for silicon the impact parameter of e.g. an incident 1 MeV carbon ion has to be smaller than 0.02 nm to remove an atom from its lattice site. The relatively small cross section for nuclear collisions and the consecutively large average distance (~ 20 nm) between displacements along a single ion track makes double or multiple hits of an atom by two or more cluster fragments rather improbable. The increase of the observed cluster effect with energy contradicts the wake riding as well as the double hit hypotheses. Therefore, we assume in the following that the cross section (per carbon atom) for point defect production by nuclear collisions is in a good approximation independent of the cluster size. This hypothesis implies that the observed effect has to be explained by an increase of the defect recombination or annealing rate with cluster size.

4.2. Defect Recombination

While the primary point defect creation mechanism by nuclear collisions is relatively simple and well understood, the development of complex defects and especially the annealing of crystal damage under irradiation is much more complex and models are not well established. Since point defects are mobile in silicon at room temperature [16] vacancies and interstitials can diffuse within an ion track and annihilate by recombination. This is possible as long as the defect density is low enough to avoid the local collapse of the crystal order in regions where a large percentage of atoms are displaced.

While, as discussed above, the number of nuclear collisions produced by a single fragment is not influenced by neighbouring tracks, the local density of primary point defects in a volume containing all tracks of one cluster impact increases with cluster size. This, in conjunction with the higher total energy dumped into this volume, may indeed influence the defect kinetics significantly. In order to construct a simple model of defect accumulation we assume that two competing processes take place along the cluster track. On the one hand the mobile primary point defects can annihilate. In a rough approximation the annihilation rate is proportional to the square of the concentration of interstitials and vacancies and

thus depends in a nonlinear way on the cluster size. On the other hand the point defects can be captured by already existing complex defects which will grow during this process. The capture rate is proportional to the number of mobile point defects. Thus, we obtain the following differential equation for the total number of point defects:

$$\frac{dn_p}{dt} = -r_r n_p^2 - r_c n_p$$

where n_p is the point defect density and r_r and r_c are constants describing the recombination and the capture process, respectively. The solution of this equation is

$$n_p(t) = \frac{r_c/r_r}{\left(\frac{r_c}{r_r n_p(0)} + 1\right) e^{r_c t} - 1}$$

The number of defects that are attached to complex defects and stay visible in the channeling experiment is then given by

$$n_c = \int_0^\infty r_c n_p(t) dt = \frac{r_c}{r_r} \ln \left(1 + \frac{r_r n_p(0)}{r_c} \right)$$

Assuming that the number of primary point defects produced by a cluster is proportional to the cluster size, i.e. $n_p(0) = b \cdot n$, one easily obtains the ratio between the number of visible defects produced by a cluster C_n and the number produced by n individual single C atoms as

$$\frac{n_c(C_n)}{n_c(C)} = \frac{\ln(1 + an)}{n \cdot \ln(1 + a)}$$

where $a = br_r/r_c$. Of course, it has to be supposed, that the particle flux during the irradiation is so low, that the recombination process is completed before the next ion hits the vicinity of the track. For the maximum current densities applied during single C atom irradiations ($1 \mu\text{A}/\text{cm}^2$) a cylinder of 3 nm radius is hit by an ion every 0.5 sec, on the average. In fig. 10 the result of the above calculation is compared to the measured cluster effect versus cluster size. The constant a has been adjusted for a best fit with the experimental data.

It is obviously possible to explain a nonlinear behavior of the defect production rate by the increased defect density along a cluster track. However, this does not explain the difference in the saturation defect density at elevated fluences. The existence of a saturation level can probably be attributed to a critical size at which complex defects stop growing (see e.g. ref. [17]). So far, we have no explanation how the size or number of complex defects could be influenced by the cluster size.

4.3. Energy Density

While point defect recombination might indeed be an important defect annealing mechanism, the driving force for this process is thermal energy. The total energy deposited along a cluster track is in a good approximation proportional to the cluster size. The development of a thermal spike and the propagation of the energy away from the track is a very complex phenomenon. In order to simplify the

problem drastically we assume that there exists an effective range r_{eff} of the energy dumped into the electronic system of the material. This range might be determined e.g. by the distance from a track at which a certain threshold temperature is reached or by the range of the produced δ -electrons. For a single C atom the average density ρ_e of deposited energy in a cylindrical volume with radius r_{eff} around the track is then given by

$$\rho_e = \frac{1}{\pi r_{eff}^2} \frac{dE}{dx}$$

For a cluster this density is higher as long as the distance between its fragments is smaller than r_{eff} . If we use the same approximation the average energy density for a cluster at a certain depth is dE/dx divided by the total crosssectional area $A(C_n)$ of the tracks as explained in fig. 11. We calculated the average area $A(C_n)$ at a depth of 150 nm below the sample surface with a Monte Carlo method for several values of r_{eff} . It was assumed that the cluster fragments straggle randomly away from their initial direction and that their distance from the original track reaches a gaussian distribution with a width given by the values displayed in fig. 1. The ratio between the average energy density in a single atom track and the energy density in a cluster track which, in this simple approximation, is equal to $A(C_n)/n\pi r_{eff}^2$ is compared to the size of the cluster effect in fig. 10 for three values of r_{eff} . The best fit with the data is obtained for r_{eff} equal to 2.0 nm.

In this simple model we essentially just compared the overlap area of all fragment tracks of a cluster. Independent of the mechanisms involved, the individual fragment tracks seem to start to interact with each other if they are closer than 2 nm. This value compares well with e.g. the 2.5 nm obtained for the range of the δ -electrons produced by 800 keV C ions in Si as calculated by a formula given in ref. [18]. Another interesting quantity for comparison is the amount of material around the ion track that could be melted by the deposited energy. Disregarding the time scales of thermalization and dissipation of the energy, i.e. under thermodynamical equilibrium conditions, the energy input corresponding to the dE/dx of a 800 keV C atom is sufficient to melt a silicon cylinder with a radius of 2.8 nm.

4.4. Cycling

The result that the defect density produced with single C atom irradiation can be lowered by postirradiation with C_n (Fig. 9) implies that already existing and stabilized defects can be annealed more effectively by clusters than by single ions. This corroborates the hypothesis that the cluster effect is not mainly caused by a lower rate of primary defect production but by a more efficient annealing process.

Conclusions

The defect concentration produced by MeV C_n projectiles in the surface region of silicon single crystals have been measured. A nonlinear behavior of the number of produced defects per carbon atom has been observed. The effect is more pronounced for high energies and large molecules. Since the primary defects produced along a single particle track are far apart (approx. 20 nm) nonlinear effects in the primary defect production rate (e.g. multiple hits of an atom by the fragments of one cluster) are considered to be negligible. Therefore, it is assumed that a difference in the annealing rate of primary point defects and/or stable complex defects must be responsible for the observed effect. This assumption is also supported by the correlation between the electronic stopping power and the size of the cluster effect (see fig. 7). On the one hand the aggregation kinetics of point defects to stable complex defects is expected to depend on the initial defect concentration along the ion track. On the other hand the deposited energy density and the associated temperature spike must strongly increase with cluster size. This, in return, influences the mobility of point defects and the annealing of existing complex crystal damage so that the effects due to the enhanced defect concentration and the increased local temperature cannot be separated.

Future research efforts will concentrate on the effects caused by larger C_n clusters ($n = 5, 6, 7, 8$) and by heavier Si_n or Ge_n clusters. Above a certain threshold it is expected that damage production due to the electronic energy loss has to take place even in semiconductor materials and metals. First experiments investigating radiation damage by C_n clusters in LiF crystals have already been conducted [19] and confirm the existence of enhanced defect production in insulators.

References

- [1] I. Yamada, H. Usui, and T. Takagi, Nucl. Instr. and Meth. **B33** (1988) 108.
- [2] M. Benguerba, A. Brunelle, S. Della-Negra, J. Depauw, H. Joret, Y. Le Beyec, M.G. Blain, E.A. Schweikert, G. Ben Assayag and P. Sudraud, Nucl. Instr. and Meth. **B62** (1991) 8.
- [3] W. Brandt, A. Ratkowski, R.H. Ritchie, Phys. Rev. Lett. **33** (1974) 1325.
- [4] H. Rothard, D. Dauvergne, M. Fallavier, K.O. Groenveld, R. Kirsch, J.C. Poizat, J. Remillieux, J.P. Thomas, in *Ionization of Solids by Heavy Particles* (R. Baragiola, Ed.), Plenum Publishing Corporation (1993).
- [5] J.F. Ziegler, J.P. Biersack, and U. Littmark, in *The Stopping and Range of Ions in Solids*, Pergamon Press, New York, 1985.
- [6] H.A. Synal, G. Bonani, R.C. Finkel, Th.R. Niklaus, M. Suter, and W. Wölfl, Nucl. Instr. and Meth. **B56/57** (1991) 864.
- [7] U.S. Fischer, M. Döbeli, M. Suter, M. Alurralde, M. Victoria, R. Gotthardt, R. Schäublin, H. Rühl, W. Wölfl, and S. Schwyn, Nucl. Instr. and Meth. **B68** (1992) 249.
- [8] W.K. Chu, J.W. Mayer, M.A. Nicolet in: *Backscattering Spectrometry*, Academic Press, 1978.
- [9] L.C. Feldman, J.W. Mayer, S.T. Picraux in: *Materials Analysis by Ion Channeling*, Academic Press 1982.
- [10] G.W. Kinchin, R.S. Pease, Rpts. Prog. Phys. **18** (1955) 1.
- [11] D.A. Thompson, R.S. Walker, Rad. Effects **36** (1978) 91.
- [12] N. Hecking, E.H. Te Kaat, Appl. Surf. Sc. **43** (1989) 87.
- [13] A. Grob, J.J. Grob, P. Siffert, Nucl. Instr. and Meth. **B62** (1992) 309.
- [14] P.J. Cooney, D.S. Gemmell, W.J. Pietsch, A.J. Ratkowski, Z. Vager, B.J. Zabransky, Phys. Rev. **A24** (1981) 746.
- [15] Z. Vager, D.S. Gemmell, Phys. Rev. Lett. **37** (1976) 1352.
- [16] P. Bogdanski, P. Mary, M. Toulemonde, Nucl. Instr. and Meth. **B62** (1992) 388.
- [17] A. Golanski, A. Grob, J.J. Grob, O.W. Holland, S.J. Pennycook, and C.W. White, Nucl. Instr. and Meth. **B62** (1992) 365.
- [18] E.J. Kobetich and R. Katz, Phys. Rev. **B170** (1968) 391.
- [19] A. Perez, M. Döbeli, H.A. Synal, Proceedings of the 7th Conference on Radiation Effects in Insulators, Nagoya, Japan, 1993, Nucl. Instr. and Meth. **B**, in press.

Tables

Ion	Source current nA	MeV beam current nA
C ₂	4000	40
C ₃	400	5
C ₄	500	5
C ₅	40	0.4

Table 1: Typical cluster currents obtained at the negative ion source and after acceleration.

Particle	Energy per C atom MeV	Fluence 10^{16} C atoms cm^{-2}	Defect Concentration %
C	0.2	1.0	22.2
C	0.8	0.1	0.98
C	0.8	0.2	1.78
C	0.8	0.5	2.59
C	0.8	1.0	2.99
C	0.8	1.5	3.09
C	1.5	0.15	1.25
C	1.5	0.25	1.12
C	1.5	0.5	1.96
C	1.5	0.8	1.88
C	1.5	1.0	2.20
C	2.0	1.0	1.36
C	3.0	0.5	1.41
C	3.0	1.45	1.52
C	3.0	2.9	1.52
C	4.0	1.0	0.81
C ₂	0.8	1.0	2.64
C ₂	4.0	1.0	0.45
C ₃	0.8	1.0	2.40
C ₄	0.2	1.0	24.3
C ₄	0.8	0.2	1.50
C ₄	0.8	0.4	1.81
C ₄	0.8	0.7	2.08
C ₄	0.8	1.15	2.29
C ₄	0.8	2.0	2.41
C ₄	2.0	1.0	0.83

Table 2: Irradiation conditions and measured defect densities (incremental χ_{min}).

Figure Captions

- Figure 1: Calculated average distance between the two fragments of a 4 MeV C_2 molecule after impact on a Si surface in function of depth. Angular straggling [5] and mutual Coulomb repulsion due to the equilibrium charge state have been taken into account. The region marked by the dotted lines has been investigated in the present experiments.
- Figure 2: Experimental set-up for cluster beam irradiation.
- Figure 3: High contrast image of C_5 cluster fragment impacts in CR-39 nuclear track detector.
- Figure 4: Random and aligned energy spectra of a virgin spot and an irradiated area ($5 \cdot 10^{15} \text{ cm}^{-2}$ 0.8 MeV C). The marked energy region represents the depth interval below the sample surface in which the defect density is compared.
- Figure 5: Measured defect concentration versus C atom fluence for C_4 clusters (crosses) and single C atoms (triangles) at an energy of 0.8 MeV per C atom.
- Figure 6: Defect saturation curves for 0.8 (triangles), 1.5 (crosses) and 3.0 MeV (diamonds) single C atom irradiation compared to 0.8 MeV C_4 irradiation (black dots).
- Figure 7: Ratio between the defect concentration produced with clusters and the one of single C atom irradiation in function of energy per C atom at a fluence of 10^{16} C atoms per cm^2 . Triangle: C_2 , diamond: C_3 , circle: C_4 , dots: P_2 molecules at 20 and 60 keV per atom (from ref. [11]). The solid line represents the electronic stopping power of carbon in silicon.

Figure 8: Ratio between the saturation defect densities of clusters and single C atoms versus cluster size at a constant energy of 0.8 MeV per C atom.

Figure 9: Defect concentrations obtained by C_4 postirradiation of samples irradiated with 10^{16}cm^{-2} 0.8 MeV C atoms. The solid curve is added to guide the eye. The dashed-dotted lines represent the single atom (a) and the C_4 (b) defect saturation levels.

Figure 10: Top: Cluster effect at 800 keV per C atom versus cluster size compared to the results obtained with a simple defect recombination model (see text). Bottom: Comparison of the measured cluster effect versus cluster size (circles) with the average energy density in a track as calculated with a simple model for an energy dissipation range of 1 nm (triangles), 2 nm (dots) and 3 nm (crosses).

Figure 11: Model of the cross section of a cluster track. For each fragment the deposited energy is dissipated into a cylinder of radius r_{eff} . The average energy density is then inverse proportional to the total area $A(C_n)$.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11