RANGES IN SILICON OF IONS WITH ATOMIC NUMBERS $62 \leqslant Z_1 \leqslant 66$ AT 100 keV

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The ranges of ions with atomic numbers $62 \leqslant Z_1 \leqslant 66$ at 100 keV in silicon have been measured. Both the projected range and standard deviation are found to vary smoothly with Z_1.

Theoretical studies of the slowing down of heavy ions in solids have produced successful predictions for ion ranges. The most comprehensive study has been that of Lindhard, Scharff and Schiøtt [1] (LSS) based on a Thomas–Fermi statistical model of the colliding atoms. The LSS theory provides data on the total ion range R and moments of the (gaussian) range distribution, such as the standard deviation ΔR. In most experiments the range distribution projected onto the initial ion direction is measured and comparisons made between the most probable projected range Rp, its standard deviation ΔRp and equivalent theoretical values. The LSS theory has proved successful for a wide variety of ions, targets and energies. Extensive compilations of range data based on this theory provide these predictions in a readily accessible form [2–4].

Deviations from the generalized LSS theory have been found experimentally [5, 6]. At high velocities where inelastic (electronic) stopping dominates the slowing-down process, the stopping power $S = -\mathrm{d}E/\mathrm{d}x$ has been found to have an oscillatory dependence on the atomic number Z_1 of the projectile. This departure of the electronic stopping power S_e from the monotonic variation assumed by LSS can be explained by introducing the outer shell electronic structure into details of the collision process [7, 8]. For channelled ions, inelastic stopping can dominate elastic stopping even at low velocities, and channelled ion ranges are consequently strongly influenced by the Z_1 oscillations of S_e.

Recently, considerable interest has been shown in experimental measurement of heavy ion ranges under conditions where elastic stopping is expected to dominate the slowing down process. The elastic (nuclear) stopping power S_n is dominant at low energies, can be related to the ion-atom potential using classical scattering theory, and for a Thomas–Fermi potential is a smoothly varying function of Z_1. In the low energy region $0.005 \lesssim \epsilon \lesssim 0.5$, the Thomas–Fermi potential can be approximated [9] by a power law potential $V(r) \propto r^{-3}$ and the total range is given by $\rho \propto \epsilon^{2/3}$ (ρ and ϵ are the range and energy parameters employed by LSS). Results [10] indicate that an $\epsilon^{2/3}$ dependence is a good approximation over most of this energy region and our own results [11] and others [12] suggest that at the lower energies, $\epsilon \lesssim 0.02$, a more screened potential is required to describe the interaction. In many cases, however, the ranges are greater than those predicted by LSS, an average discrepancy being $\sim 30\%$ at $\epsilon \sim 0.1$.

Recent measurements [13, 14] indicate that ion ranges, even in the nuclear stopping regime, are not a smooth function of Z_1 as predicted by LSS for the Thomas–Fermi potential. Ranges of 100 keV ions in Al for $55 < Z < 79$ are greater than theoretical predictions by up to a factor of 1.9 and, in addition, show a sharp variation with Z_1. It has been suggested that similar oscillatory behaviour should occur for ion ranges in Si [17]. These results have been explained [14] by an ion-atom potential that does not vary smoothly with the atomic number of the projectile or, alternatively, by introducing a further energy loss mechanism not included in previous theories [1]. It has been suggested [14] that in collisions between partners which have matching inner-shell energy levels, the cross-section for excitation of electrons from the matched levels could become large. In addition [14], frequent collisions may be expected to produce outer

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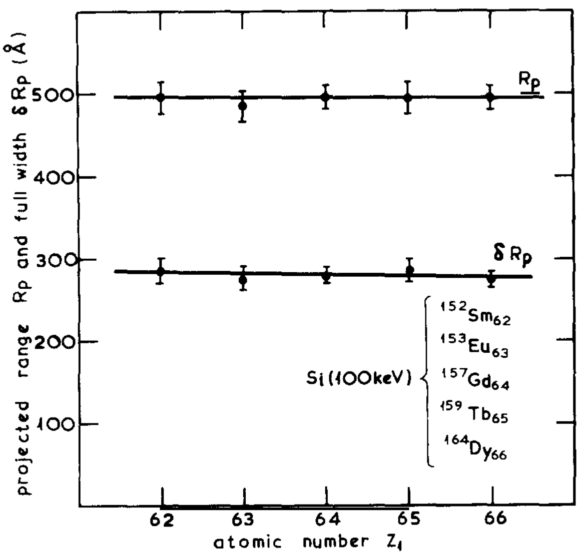

Fig. 1. The most probable range Rp and the range distribution width δRp for various ions in silicon at 100 keV.

shell vacancies and this would increase the inner-shell excitation cross-sections. Also the presence of inner-shell excitations during collisions changes the potential, affects the scattering angle and could increase the nuclear stopping power [14].

In a previous publication [11] we have reported on the projected range Rp and standard deviation ΔRp of low energy heavy ions in silicon. In the present letter we have continued these measurements to specifically cover the projectiles with $62 \leqslant Z_1 \leqslant 66$, which includes ions for which range oscillations would be expected to occur when implanted into silicon [17]. All implantations were carried out at 100 keV using a single isotope for each species. A dose of 5×10^{14} ions/cm^2, sufficient to amorphise the silicon, but sufficiently low to avoid broadening of the range profile, was implanted at 7° off the major ⟨110⟩ crystallographic direction to minimise channelling. Range profiles were measured using Rutherford backscattering of 2 MeV He^+ ions with a solid state detector of energy resolution 16 keV FwHm. The depth resolution was improved by a factor of 7 over more conventional methods, by employing an analysing beam that entered and left at small angles to the target surface [15]. The results for the most probable projected range Rp and the full width (at $e^{-1/2}$) δRp as a function of Z_1 are shown in fig. 1. Rutherford backscattering spectra were converted to depth profiles using tabulated stopping power data [16] and projected ranges were calculated using a silicon density of 2.33 g/cm^3. The error bars shown for each point include the usual statistical counting uncertainties, together with errors due to locating the target surface and the peak of the distribution. The limitations of the energy resolution of the measuring system, build-up of carbon contamination during Rutherfod analysis, and pile-up of low energy pulses also contribute to the nett error. The data of fig. 1 is in good agreement with our previous results [11] with Rp greater than tabulated values [4] based on LSS. At 100 keV Dy, for example, has a predicted Rp of 411 Å, to be compared with the measured value of 495 Å. Both measured quantities shown in fig. 1 are, however, a smoothly varying function of Z_1 within the experimental error limits of ± 20 Å.

The data does not therefore show the oscillatory behaviour predicted for Si [17], and the additional stopping power term due to matching of atomic energy levels [14] would appear to be negligible in this material. The present results are, however, entirely for silicon substrates and the proposed excitation model is supported by more extensive data for aluminium [13]. Further work is therefore in progress to examine the differences between these two substrates and their influence on the effects of inner-shell excitations during collisions with heavy ions.

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