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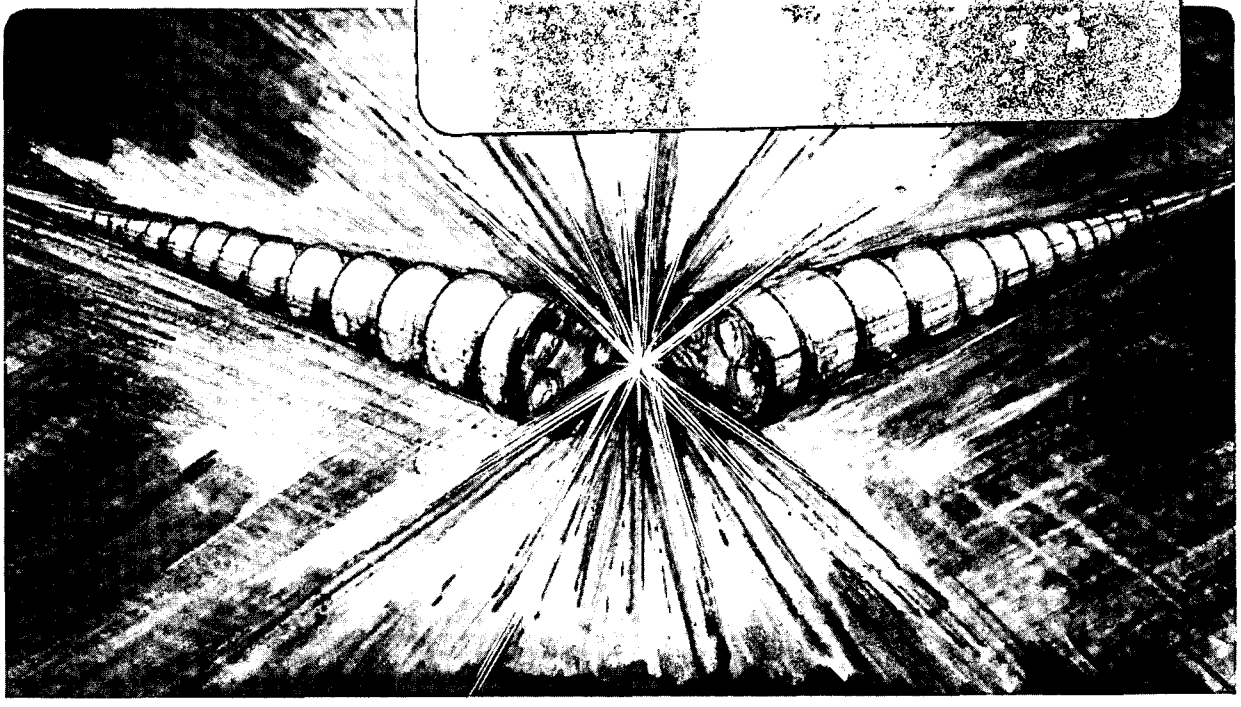

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HIGH DOSE URANIUM ION IMPLANTATION INTO SILICON*

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ABSTRACT

Implantation of uranium ions into silicon to a maximum dose of 6×10^{16} atoms/cm^2, with a maximum concentration of 6×10^{21} atoms/cm^3, has been carried out. This concentration corresponds to 12 atomic percent of uranium in the silicon host material. The implanted uranium content was measured by Rutherford backscattering and confirmed by a measurement of the alpha-particle activity of the buried uranium layer. The range and straggling of the uranium, and sputtering of the silicon target by uranium, were measured and are compared with theoretical estimates. The implantation was performed at an ion mean energy of 157 keV using a new kind of high current metal ion source.

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The implantation of gaseous ions into material surfaces, both semiconductor and metallurgical, is a well-developed technique, and high concentrations of the implantant species can be produced. Recently high dose implantations in semiconductors have stimulated particular interest in the area of semiconductor-on-insulator (SOI) structures. Buried layers of oxides and nitrides [1] in silicon crystals have been produced by high dose ($\sim 10^{18}$ at/cm^2) implantations of oxygen and nitrogen. High-dose implants require a high current ion source to produce the intense flux of implantant ions. Impressive advances have been made in the technology of production of high current beams of gaseous species such as hydrogen and deuterium as required for the controlled fusion program, as well as of other gaseous ions [2-4]. The production of high current beams from solids has not witnessed similar progress. Conventionally these kinds of sources make use of surface ionization [5,6], evaporation [5,7-9], or sputtering [5,10,11] of the solid material into the gaseous/plasma state, and the beam intensity is inherently limited. Thus high-dose implantation of metal ions into material surfaces has not been so readily achieved.

We report here on the high dose implantation of uranium ions into silicon. Uranium implants have been reported on previously at doses of about 10^{14} at/cm^2 [12-14]. In the present work we used a new kind of high current metal ion source, called the MEVVA (metal vapor vacuum arc) ion source, to produce uranium implants at a dose of over 5×10^{16} at/cm^2.

The MEVVA ion source has been described elsewhere [15-18]. Briefly, in this source we make use of the intense plume of highly ionized metal plasma that is created at the cathode spots of a metal vapor vacuum arc discharge to provide the "plasma feedstock" from which the ion beam is extracted. The quasi-neutral plasma plumes away from the cathode toward the anode, persisting for the duration of the arc current drive. The anode of the discharge is located on-axis with respect to the cylindrical cathode and has a central hole through which a part of the plasma plume streams. The plasma drifts through the post-anode region to a set of grids that comprise the ion extractor - a three-grid, accel-decel, multi-aperture design. A schematic of the source that we've used for the present work is shown in Figure 1. This is the device called MEVVA IIb. The extractor diameter is 2 cm, as is the initial beam

diameter. For the work described here, the beam extraction voltage was 60 kV and the total extracted ion beam current was about 40 mA. The source was operated in a pulsed mode, with pulse width about 250 μs and repetition frequency 5 pps; at present the MEVVA II source runs at low duty cycle, as required for injection of beams into the LBL heavy ion synchrotron, the Bevalac [19,20]; this is not an inherent limitation of the source. We have produced high current beams of a wide variety of metallic species, including Mg, Al, Si, Ti, Cr, Fe, Co, Ni, Cu, Zn, Zr, Nb, Mo, Rh, Pd, Ag, Gd, Ho, Ta, W, Pt, Au, Th and U.

Beam composition has been measured with a time-of-flight diagnostic [21]. A submicrosecond sample of the beam pulse is drifted down a field-free region where it separates into its different charge-to-mass components, and the arrival times of the Q/A-separated components are detected by a Faraday cup, thus providing a measurement of the amplitudes of the current in the individual charge state components of the beam. A uranium charge state distribution (CSD) is shown in Figure 2; note that the signal shown is electrical current, and one needs to divide the amplitudes shown by the charge state $\bar{Q}$ to obtain particle current. The peak charge state is U^{3+} (54% of the total beam particle current), and the mean charge state, $\bar{Q}$, is 2.62. Thus the CSD-weighted ion mean energy is $\bar{Q}V$ = 157 keV.

The target was a 4-inch silicon wafer located at a distance of 45 cm from the ion source extractor and tilted off-normal by about 10° so as to avoid channeling. The vacuum system was cryogenically pumped and oil free, with a pressure in the main chamber of about 1×10^{-6} Torr. The wafer was cooled only by thermal conduction of the support structure, and the beam repetition rate was limited to 5 pps to avoid overheating of the target. The beam current incident on the wafer was approximately 20 ma; a total of 330,000 shots was accumulated.

The uranium concentration profile across the wafer was measured by Rutherford backscattering spectrometry (RBS) [22] using a 2.0 MeV $^{4}He^{+}$ beam. The damage of the silicon crystal induced by the implantation was also investigated by ion channeling with 1.5 MeV $^{4}He^{+}$. The results of these measurements are shown in Table I, where the dose, peak concentration, range,

and straggling of the implanted uranium atoms are given for several positions across the wafer. The measured dose and peak concentration are plotted as a function of wafer location in Fig. 3.

The uranium dose was also measured by counting the alpha particle activity of a small sample of the implanted wafer. The integrated number of counts in the energy range near 4.1 - 4.2 MeV, corresponding to $U \rightarrow Th + \alpha$ disintegrations, over a 24 hour period, was 5,650. For the known counter efficiency of approximately 16%, this corresponds to $(7.5 \pm 1.5) \times 10^{16}$ U^{238} at/cm^2, in good agreement with the dose measured by RBS at this wafer location, $(5.8 \pm 0.2) \times 10^{16}$ at/cm^2.

The range and straggling measurements have a considerable uncertainty associated with them because of (i) removal of surface material through sputtering of the silicon by the incident uranium beam, (ii) departure of the implanted uranium depth profile from Gaussian due to the high concentration, and (iii) departure of the implanted uranium depth profile from Gaussian due to the charge state structure and hence energy structure of the incident ion beam. These are inherent features and the range and straggling are ill-defined in the present case. Here we chose to measure the range as the distance from the surface to the maximum of the uranium profile and the straggling as the standard deviation of the Gaussian that best fits the sides of the measured profile (ie, discounting the broadened top of the profile). These are the measurements shown in Table I. The range error due to surface erosion by sputtering can be removed by extrapolating backwards to the zero-dose limit as indicated in Fig. 4. A linear regression provides an "extrapolated zero-dose" estimate of the range, R_p(limit dose $\rightarrow$ 0), of 500 A.

The concentration profile was calculated for each of the charge state species and its corresponding energy - U^+ at 60 keV, U^{2+} at 120 keV, U^{3+} at 180 keV and U^{4+} at 240 keV - using the TRIM code developed by Biersack and Ziegler [23]. The resultant depth profile for all charge states combined was then obtained by summing the individual calculated profiles weighted according to the measured charge state fractions. This yields an effective range of 560 A and an effective straggling of approximately 200 A. One can also estimate a

range and straggling by assuming the beam to be mono-energetic at the CSD-weighted mean energy of 157 keV, and using the TRIM code; this yields a range of 611 A and a straggling of 125 A.

A comparison of the measured range and straggling with the predicted values is shown in Table II. The theoretical values obtained by including the beam charge state structure into the TRIM calculation provide a significantly better fit than do those obtained by by assuming a mono-energetic beam of the mean charge state.

We can estimate the sputtering yield implied by the surface erosion rate. Table III shows the dose dependence of the sputtering yield of silicon by uranium measured in this way. The sputtering yield Y calculated using the model developed by Sigmund [24] is approximately 6 silicon atoms per incident uranium ion. This is to be compared to the experimental value of $Y = 4.0$ for the lowest dose case (1.5×10^{16} at/cm^2); for the higher dose implants, the measured values of Y are significantly lower than the theoretical values. This dose dependence of Y for various ion-target combinations has been pointed out by a number of authors [25-28]. Andersen and Bay [28,29] suggested that this effect is caused by surface changes in the target induced by the projectile ions, including changes in surface binding energy and surface topography as well as the formation of precipitations and bubbles in the target material. A detailed investigation of the dose effect of the sputtering of silicon by uranium is in progress.

Figure 5 shows the aligned RBS spectra of the <111> Si samples taken from the center and the edge of the uranium implanted wafer. The random and aligned spectra of an unimplanted <111> Si sample are also shown in the figure for comparison. The aligned spectra of the implanted samples indicate that the implanted layers became amorphous over a depth of ~2000 A for the sample taken from the center of the wafer and ~1400 A for that taken from the edge of the wafer. Since a higher dose of uranium is measured at the center (~6×10^{16} at/cm^2) than at the edge (~1×10^{16} at/cm^2) of the implanted wafer, the damage of the silicon lattice induced by the implantation process is dependent on the dose of the uranium. However, it should be noted that the thicknesses of the amorphous layers measured here are smaller than the actual values because of the sputtering effect mentioned above.

The results reported on here demonstrate the kind of implantation that can be done using the MEVVA high current metal ion source. This source can produce high current beams of virtually all the solid metals, including the refractory metals, and can thus be of use in carrying out high dose implants of these metal species. The duty cycle at which the source can be operated, and so also the average beam current, will be upgraded in the near future, and we anticipate that this kind of ion source will find application to metal ion surface modification work.

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Table I Dose, peak concentration, range, and straggling, for several radial positions across the wafer, measured by RBS.

Radius (cm)	Dose (10^{16} cm^{-2})	Concentration (10^{21} cm^{-3})	Range (A)	Straggling (A)
-4.6	1.5 ± 0.05	2.2 ± 0.1	440 ± 50	220 ± 30
-2.5	5.8 ± 0.2	6.2 ± 0.3	300 ± 50	250 ± 30
-0.2	5.9 ± 0.2	5.9 ± 0.3	300 ± 50	280 ± 30
+1.5	6.1 ± 0.2	6.3 ± 0.3	280 ± 50	280 ± 30
+3.3	3.4 ± 0.1	4.4 ± 0.2	400 ± 50	280 ± 30

Table II Comparison of the RBS-measured range and straggling with predictions based on the component charge state penetrations, and on the penetration of ions at the weighted-mean energy.
High dose: 6 x 10^{16} at/cm^2.
Low dose limit: Extrapolated linearly back to the zero-dose limit as indicated in Fig. 3.

	Measured (RBS)		Calculated (TRIM)	
	High dose	Low dose limit	With Q structure	157 keV
Range (A) :	300	500	560	611
Straggling (A):	270	270	200	125

Table III Sputtering yield, Y, implied by the measured surface erosion, as a function of dose. Erosion is calculated from the difference between the measured apparent range and the TRIM-calculated range of 560 A.

Dose (10^{16} at/cm^2)	Range (A)	Erosion (A)	Sputtering Yield Y
1.5	440	120	4.0
3.4	400	160	2.3
5.8	300	260	2.3
5.9	300	260	2.2
6.1	280	280	2.3

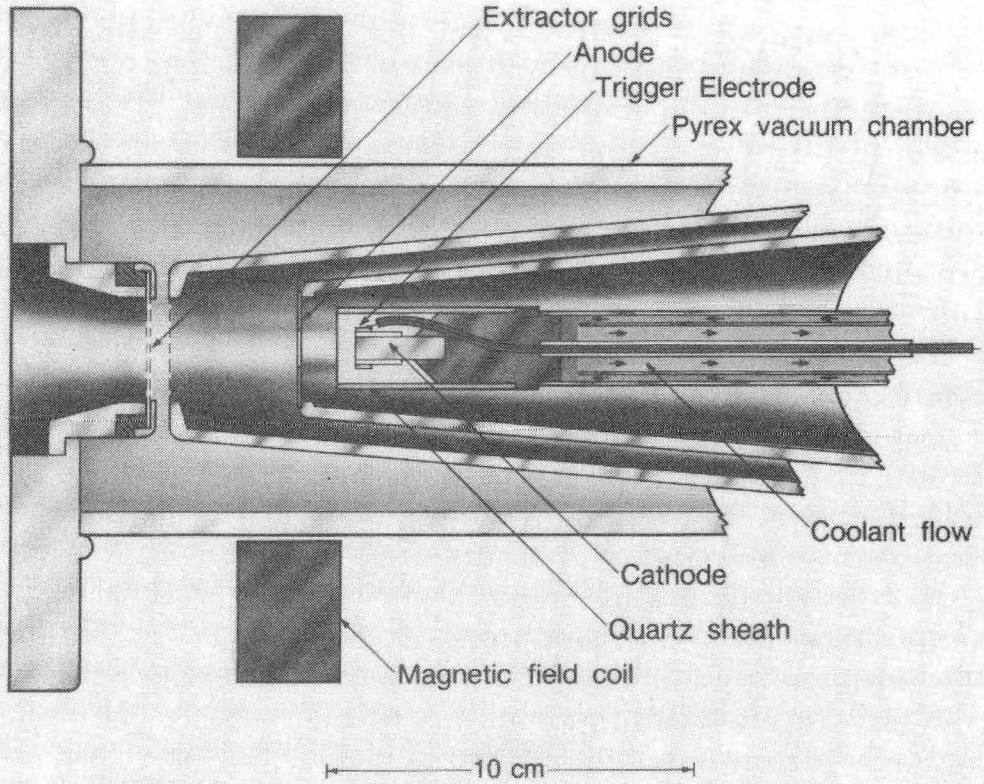

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Fig. 1 Schematic of the MEVVA IIb high current metal ion source.

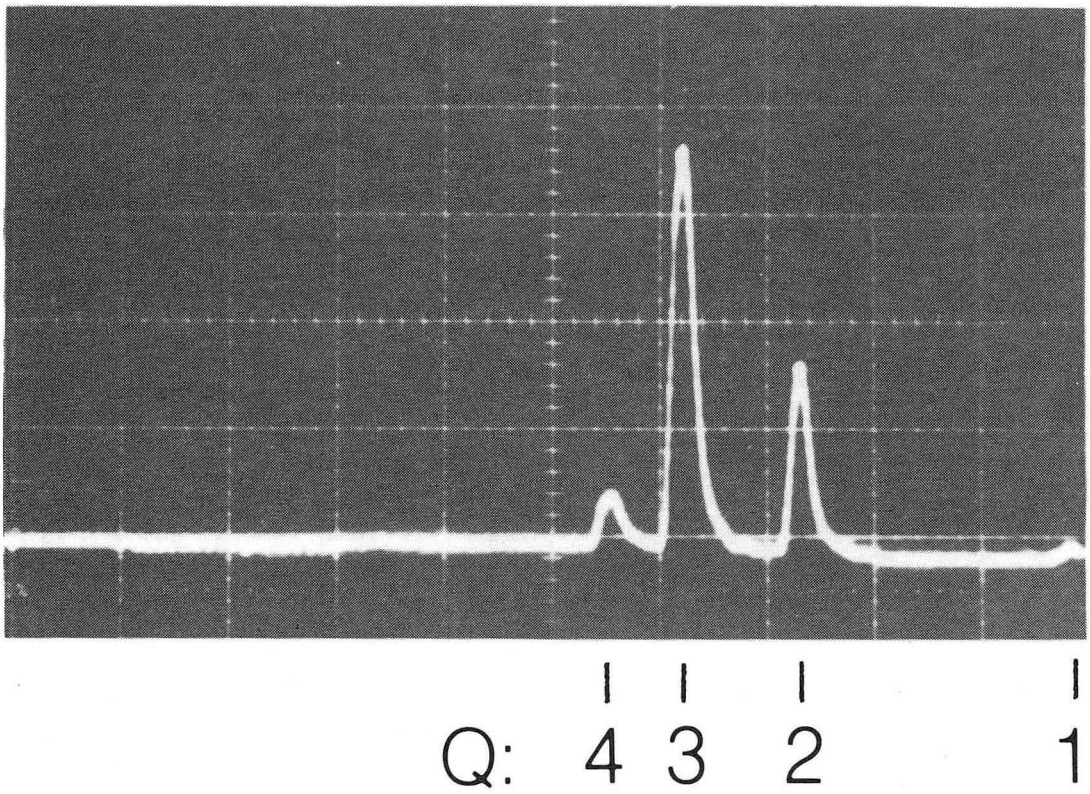

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Fig. 2 Measured charge state distribution for uranium ion beam. The vertical scale is electrical current measured by a Faraday cup.

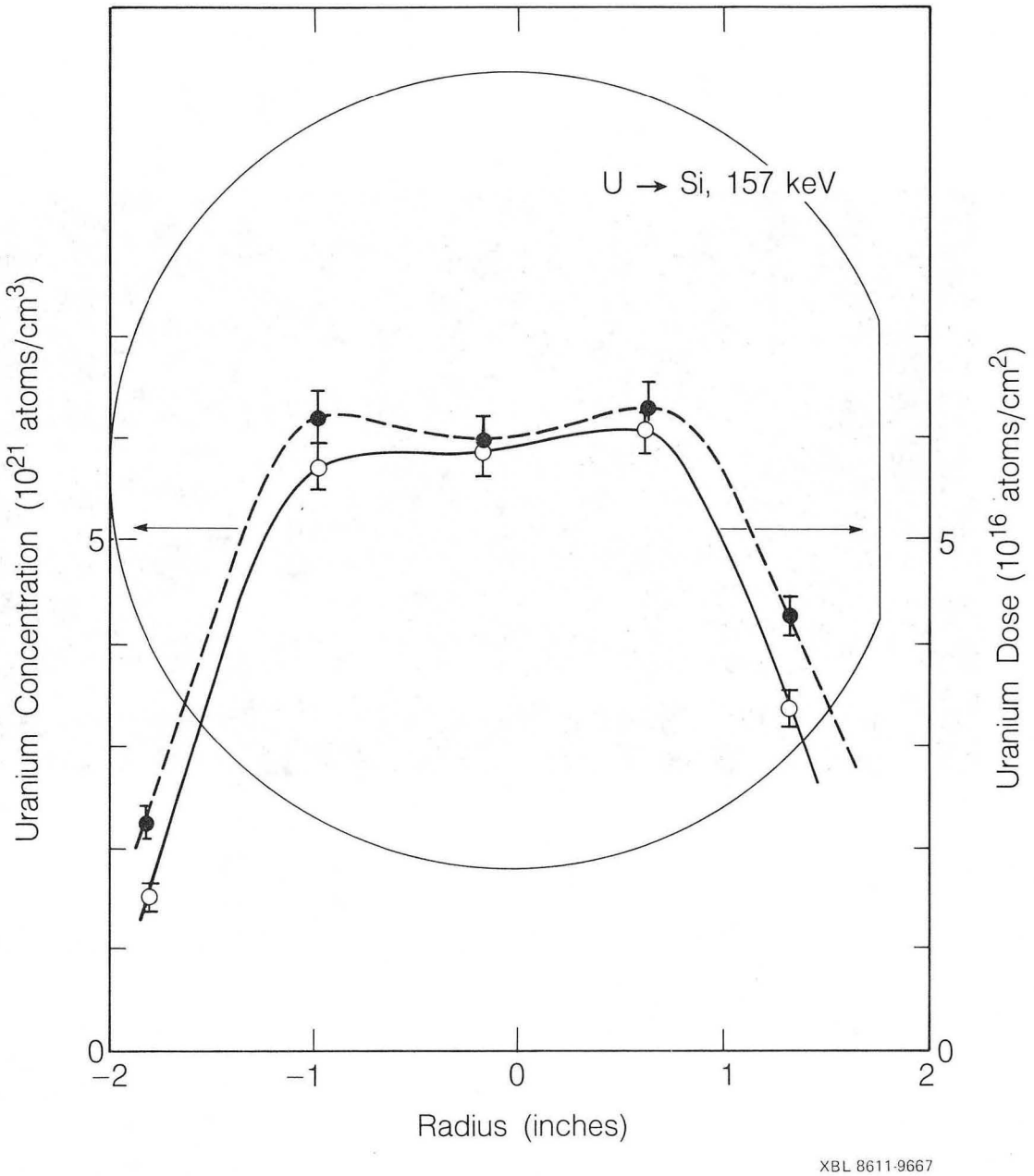

Fig. 3 Implanted uranium concentration and dose as a function of position across the silicon wafer, measured by RBS.

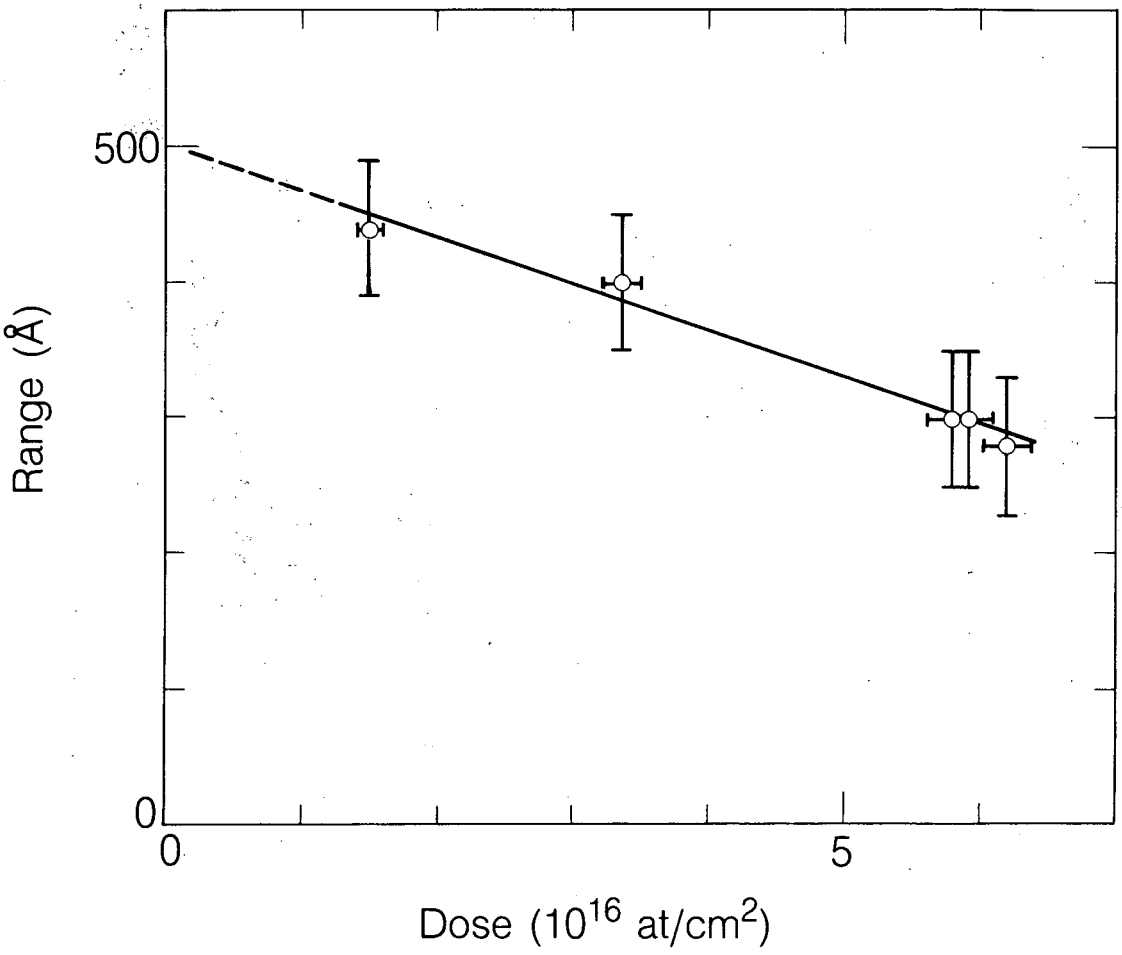

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Fig. 4 Measured range as a function of dose.

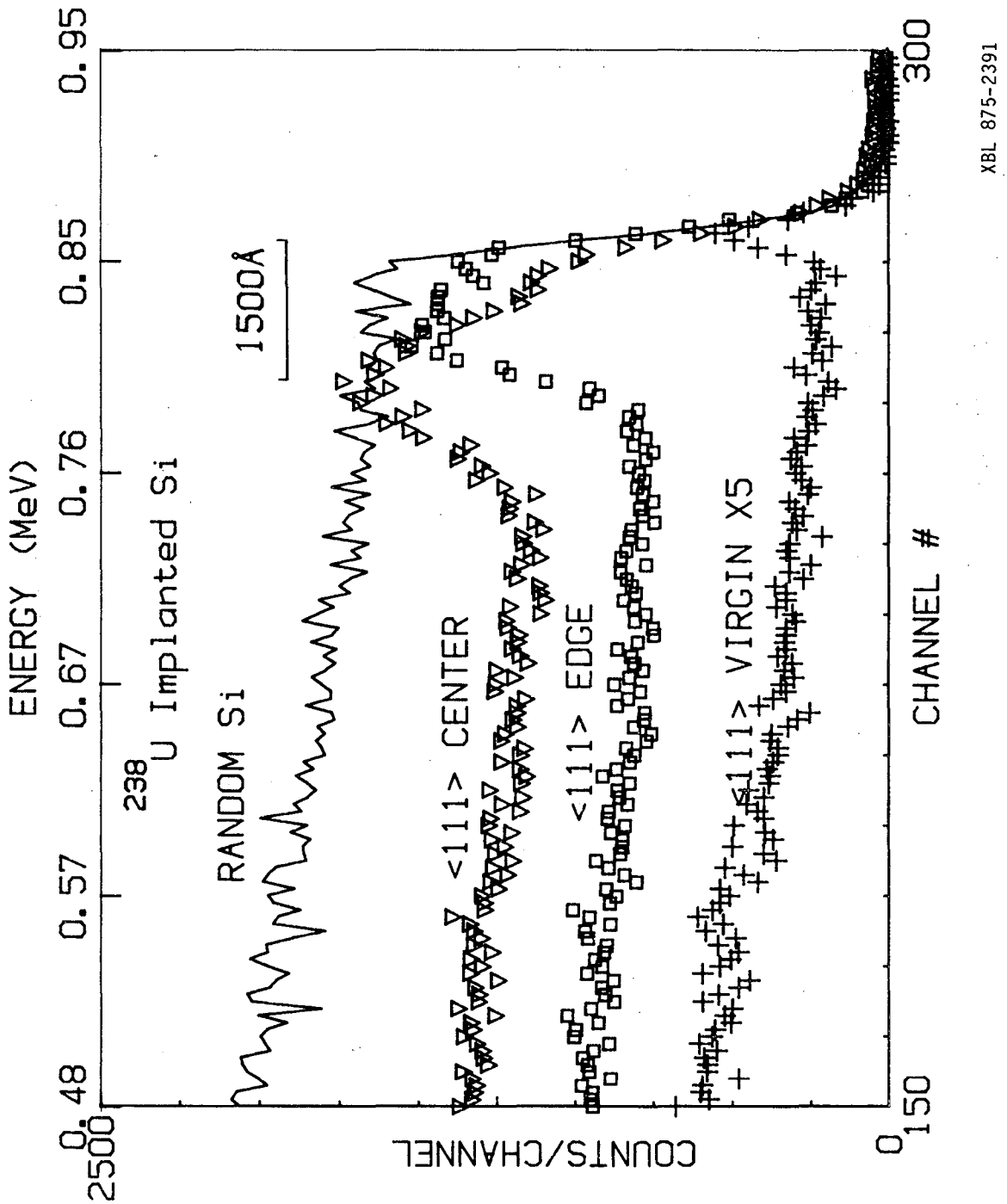

Fig. 5 The aligned RBS spectra of the <111> Si samples tasken from the center and the edge of the implanted wafer. The random and aligned spectra of unimplanted <111> Si are also shown.

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