## 2.3 Penetration depth of lattice disorder produced by ion implantation in semiconductors

G. DELLA MEA, A. V. DRIGO, P. MAZZOLDI, G. NARDELLI and R. ZANNONI
*Istituto di Fisica, Padova, and Laboratori Nazionali di Legnaro, Italy*

## 2.4 A dechanneling model for the description of the temperature behaviour of the sputtering ratio

H. E. ROOSENDAAL, J. J. P. ELICH and D. ONDERDELINDEN, *FOM-Instituut voor Atoom- en Molecuulfysica, Kruislaan 407, Amsterdam, The Netherlands*

## 2.5 Radiation damage, annealing and bubble formation in $UO_2$ induced by ion bombardment

B. NAVINŠEK and V. KRAŠEVEC, *Institute „Jožef Stefan", Ljubljana, Yugoslavia*

Radition damage in $UO_2$ has been studied mainly by means of neutron irradiation. Ion bombardment has been used for gas precipitation investigations by Barnes and Mazey[1)] (2 keV $He^+$ ions, epitaxial thin films of $UO_2$) and by Williamson and Cornell[2)] (100 keV $Kr^+$ ions, synthetic $UO_2$). Also Matzke[3)] and Cornell and Banister[4)] found small bubbles in $UO_2$ bombarded by heavy ions (40 keV $Xe^+$ ions, 100 keV $Kr^+$ inos.). For our studies we used arc melted $UO_2$ pellets. A very effective method of chemical polishing has been used. The results have been correlated to the neutron induced radiation damage and bubble formation given in the literature[5)].

Thin foils of polycrystalline $UO_2$ were chemically polished to electron transparency and bombarded with 4 keV $A^+$ and 150 keV $H^+$ ions. The ion dose varied from $10^{15}$ to $10^{18}$ ions/cm$^2$. Irradiation temperature was 20°C, while the annealing was studied at temperatures of 900, 1200 and 1500 °C.

Electron microscope observations have shown that 4 keV $A^+$ ions produced damage in $UO_2$ in the form of large defect clusters, dislocations and complex dislocation tangles and networks. The intensity of damage increased with ion dose, but a „saturation" effect has been observed for all different orientations of grains at doses of approx. $5 \times 10^{17}$ ions/cm$^2$. In Fig. 1 the damage in a $UO_2$

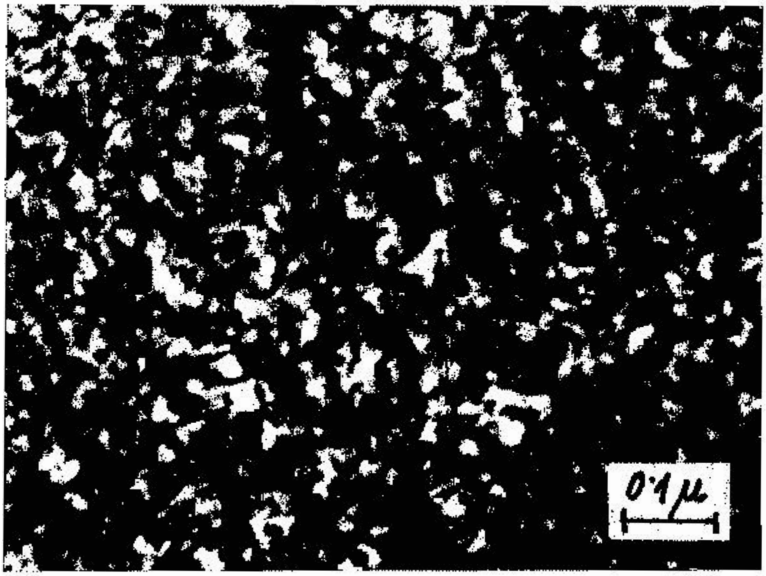


Fig. 1 Damage in $UO_2$ foil, bombarded with 4 keV $A^+$ ions; ion dose $5 \times 10^{15}$ ions/cm$^2$.

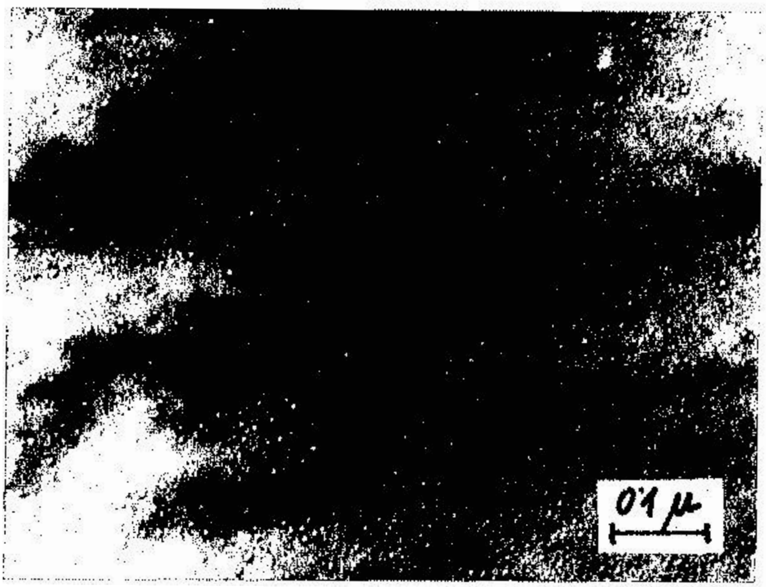


Fig. 2 Argon bubbles in $UO_2$, bombarded with 4 keV $A^+$ ions (ion dose $1.5 \times 10^{18}$ ions/cm$^2$) and annealed 1 hour at 1500 °C.

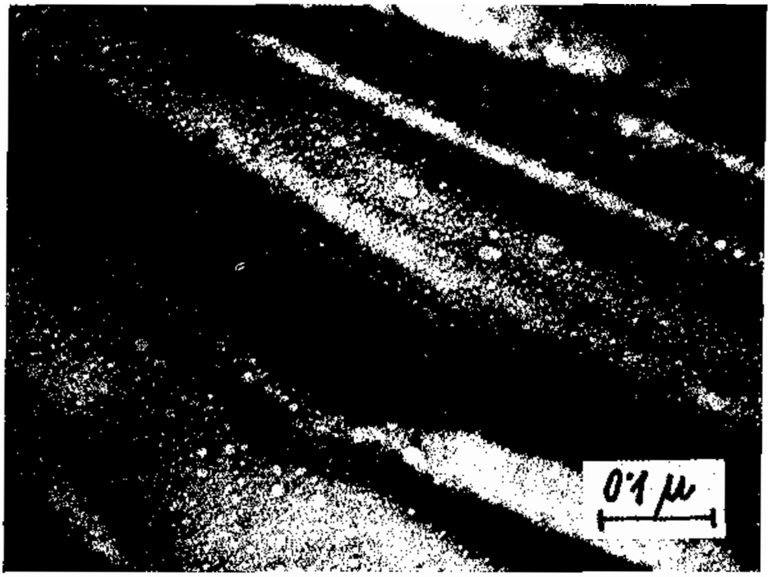


Fig. 3 Coalescence of small argon bubbles in $UO_2$ after heating with an intense electron beam in electron microscope ($UO_2$ bombarded with 4 keV $A^+$ ions; ion dose $7.5 \times 10^{16}$).

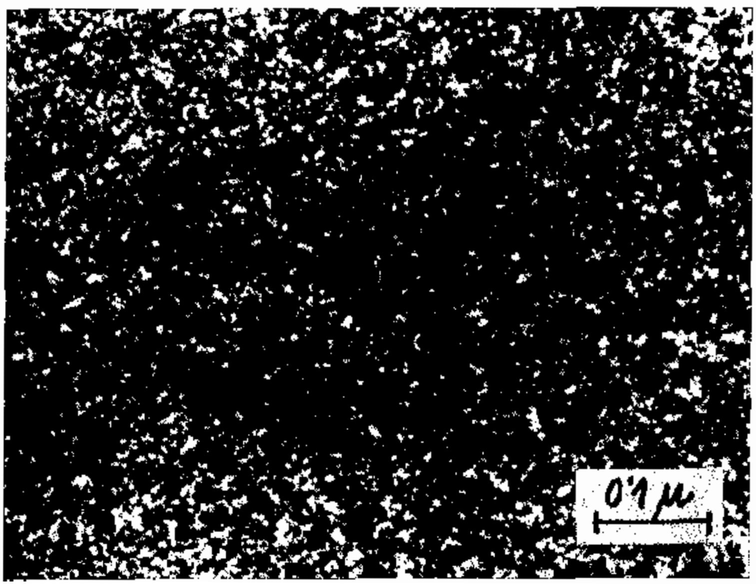


Fig. 4 Damage in $UO_2$ foil, bombarded with 150 keV $H^+$ ions; ion dose $5 \times 10^{15}$ ions/cm$^2$.

thin foil is shown, after bombardment with 4 keV $A^+$ ions and with an ion dose of $5 \times 10^{15}$ ions/cm$^2$. Annealing of bombarded $UO_2$ specimens in a vacuum of $10^{-7}$ torr for 1 hour at 900 °C caused some effect only for the highest doses, but the annealing of defects after 1 hour at 1200 °C was nearly complete. Only a few large dislocations remained and part of the argon was precipitated in the form of small gas bubbles. The bubbles were homogenously distributed in the $UO_2$ foil and were 80—100 Å in diameter (Fig. 2). Additional heating of bombarded foils with an intense electron beam in a Siemens electron microscope produced coalescence of these small bubbles, some of larger bubbles having regular polyhedral form (Fig. 3). As the time of heating increased, the total number of bubbles decreased and the average diameter of bubbles increased simultaneously.

In (110) oriented $UO_2$ foil, the shape of gas precipitates was roughly spherical when the dimensions of the precipitates were smaller than 100 Å. After the development of (111) planes there exist mainly rectangular forms with edge dimensions approx. up to 150 Å. Larger polyhedral bubbles had hexagonal forms with the longest edge in general parallel to the (110) direction. In (111) oriented foils, mainly precipitates of spherical shape or rounded corners with an average diameter less than 150 Å have been found.

After bombardment of $UO_2$ foils with keV $H^+$ ions (doses from $3 \times 10^{15}$ to $1 \times 10^{17}$ ions/cm$^2$), very homogenously distributed small defect clusters (dimensions 25—50 Å) were observed (Fig. 4). After partial annealing, parallel to the increased dimensions of defects, some well resolved dislocation loops were found. In proton bombarded $UO_2$ specimens, precipitation of gas in the form of gas bubbles was not observed, even in the case when specimens had received the highest doses at low energies (50 keV).

One can conclude that low energy ion bombardment produces a high density of defects in $UO_2$ and therefore represents a convenient way of studying damage and annealing in ceramic fuels.

## References

1) R. S. Barnes and D. J. Mazey, III. Eur. Conf. El. Micr., Prague 1964, p. 197;

2) R. M. Cornell and G. K. Williamson, J. Nucl. Mat. **17** (1965) 200;

3) H. Matzke, J. Nucl. Mat. 30 (1969). 107;

4) B. T. Bradbury and B. R. Frost. Radiation Effects in Ceramic Fuels, Gordon & Breach, New York 1965, p. 157;

5) B. Navinšek, The Study of Radiation Damage in Ceramic Fuels, NIJS Report — DP 159, November 1969.