Implantation of 18O+ ions in channelling directions of aluminium, copper and nickel single crystals - II. - Stopping power determination by maximum range measurements

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Implantation of $^{18}O^+$ ions in channelling directions of aluminium, copper and nickel single crystals

II. — Stopping power determination by maximum range measurements

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Résumé. — Les pénétrations maximum des ions oxygène canalisés dans des monocristaux d'aluminium, de nickel et de cuivre sont déterminées à partir des profils d'implantation obtenus pour des énergies variant entre 10 et 45 keV. Ces mesures sont utilisées pour déterminer les valeurs correspondantes du pouvoir d'arrêt. Les résultats mettent en évidence l'influence de la direction de canalisation et de la nature de la cible sur les pertes d'énergie électroniques. Les résultats expérimentaux sont comparés à des valeurs théoriques calculées à l'aide de la théorie de Firsov appliquée à la canalisation ; les ordres de grandeur obtenus sont comparables.

Abstract. — The maximum ranges of channelled oxygen ions have been measured, for energies varying between 10 to 45 keV, on implantation profiles obtained in Al, Ni and Cu single crystals. These measurements are used to determine the corresponding values of the stopping power. The results show the influence of the direction of channelling and of the nature of the target on electronic energy losses. The experimental values are compared to theoretical values calculated with Firsov's theory applied to channelling ; order of magnitude agreement is obtained.

1. **Introduction.** — The experimental procedure described in paper I has been developed in order to measure the stopping power of Cu, Ni, Al in some channelling directions. As the energy of the incoming ions is rather low (10-45 keV), the energy losses of the channelled ions can not be measured directly and they are deduced from maximum range measurements. These determinations are made on the implantation profiles corresponding to the various axial channelling directions investigated. A comparative study of the stopping power of these three f.c.c. metals is made for the same crystallographic directions of implantation so as to characterize the influence of the atomic number Z_2 of the target. These values of Z_2 are very close for nickel (28) and copper (29) and much smaller for aluminium (13). As we are interested in oxygen implantation we have studied the channelling behaviour of $^{18}O^+$ ions.

2. **Relation between the maximum range and the stopping power.** — The range of the ions (R) depends on the energy losses experienced by the particles and a relation exists between R, the stopping power $-\,dE/dx$ [1] and the energy (E_0) of the ions :

$$R = \int_0^{E_0} \frac{dE}{-(dE/dx)} \qquad (1)$$

When the ion trajectories are random, the only values that are measurable experimentally are the ion ranges R_p projected along the direction of implantation and R_p is different from R. In the case of channelling, it is possible to measure the maximum range corresponding to the best channelled ions which move parallel to the direction of implantation during their whole slowing down time. This maximum range R_{max} is the most reproducible parameter of the channelled trajectories and is related to the stopping power by relation (1), so dE/dx may be calculated by differentiating the curve giving R_{max} *versus* E_0 [2].

In the low energy range, the slowing down of channelled particles is chiefly governed by electronic energy losses and the stopping power is given by the following relation :

$$-\frac{dE}{dx} = kE^p \qquad (2)$$

with $1 > p > 0$.

The relations (1) and (2) give a linear relationship [3, 4] between R_{max} and E_0^{1-p} when the most important energy losses for the energy E_0 are of electronic nature. By theoretical calculations [5, 6], it has been demonstrated that the electronic energy losses are proportional to ion velocity and p is equal to 0.5 in relation (2). For these conditions the linear relationship between R_{max} and E_0^{1-p} may be written [3]

$$R_{max} = (2/k)\, E_0^{0.5} + B \qquad (3)$$

where B is a constant.

Some experimental measurements of the electronic stopping power show that p varies with the atomic number of the incident ions and may differ noticeably from 0.5 [7, 8, 9]. On the other hand experimental values of R_{max} measured for W and Cu [3, 1] exhibit a linear relationship *versus* $E_0^{0.5}$.

3. **Results.** — 3.1 MAXIMUM RANGE DETERMINATION. — The implantation profiles (paper I) generally exhibit a sharp decrease for the deep penetrations, but as the secondary ion emission yield varies with the nature of the target, the range of variation for secondary ion current is more important for oxygen implanted in aluminium than for copper and nickel (cf. § 4, paper I). The cut off is noticeable on profiles obtained on aluminium when the secondary ion current intensity decreases by five decades, the corresponding penetration depth is taken as the maximum range of penetration of channelled ions : R_{max}. Consequently it seems reasonable to define for each profile R_{max} as being the value of the depth for which the intensity is 10^5 times smaller than the maximum intensity of the secondary ion current.

The values of the intensity measured for copper, nickel and sometimes for aluminium do not decrease by five decades, so it is necessary to extrapolate the values of intensity *versus* depth by fitting the end of the profile to a polynomial form (Fig. 1).

In a previous paper [3] dealing with measurements on copper, R_{max} has been chosen as the penetration depth corresponding to the intensity which has decreased over four decades. To have comparable results on the three metals it seems reasonable to take the same intensity criterion ($10^{-5}\ I_{max}$) to determine the value of R_{max}. This does not imply a noticeable modification of the results since the difference between the values of R_{max} corresponding to $10^{-5}\ I_{max}$ or $10^{-4}\ I_{max}$ is smaller than the experimental uncertainty for the depth measurements.

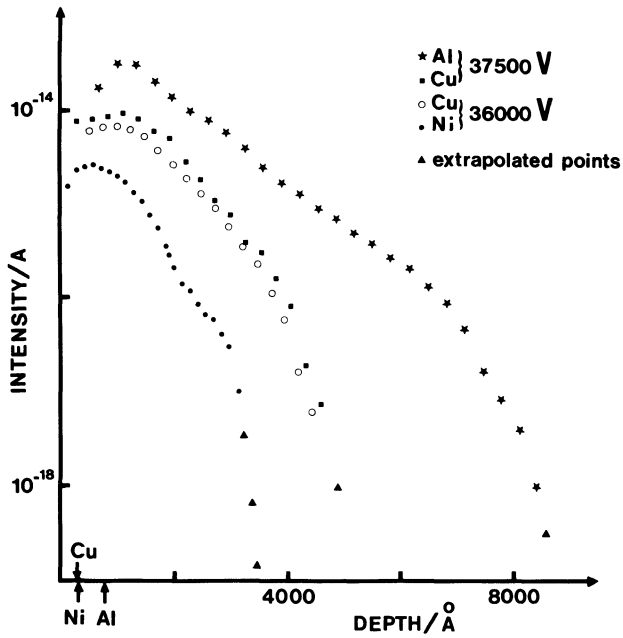

Fig. 1. — Depth concentration profiles of ^{18}O implanted along a ⟨ 110 ⟩ direction in copper, nickel and aluminium single crystals. Some points calculated by polynomial extrapolation have been added. The secondary ion current $I(^{18}O^-)$, proportional to oxygen concentration, is measured *versus* eroded depth with an ion probe microanalyser.

The experimental results obtained for copper, nickel and aluminium are given in table I : the different values of R_{max} have been measured for various energies E_0 of the incident oxygen ions. The experimental uncertainties on the determination of R_{max} are also mentioned in this table : they vary between 5 % and 10 %. As the values of E_0 are known with a better accuracy, the error for the energy is negligible.

Table I. — *Values of R_{max} measured for oxygen ions implanted along ⟨ 110 ⟩ and ⟨ 100 ⟩ directions in copper and aluminium and a ⟨ 110 ⟩ direction in nickel. E_0 is the energy of the incident ions.*

Copper			Nickel		Aluminium		
	R_{max}/Å			R_{max}/Å		R_{max}/Å	
E_0/keV	⟨ 110 ⟩	⟨ 100 ⟩	E_0/keV	⟨ 110 ⟩	E_0/keV	⟨ 110 ⟩	⟨ 100 ⟩
—	—	—	—	—	—	—	—
42.8	5 200 ± 250	4 000 ± 200					
37.5	4 850 ± 250	3 700 ± 200			37.5	8 300 ± 800	6 500 ± 600
36	4 650 ± 250		36	3 500 ± 400	27.3	6 200 ± 400	
28.4	4 050 ± 250				26		5 000 ± 500
27.5	4 000 ± 250	3 000 ± 200	25	3 050 ± 400	18.4	4 500 ± 400	
17	3 000 ± 200		16	2 250 ± 270	16.6		3 600 ± 350
11.3	2 450 ± 200	1 500 ± 150	11	1 800 ± 270	11.3	2 600 ± 350	2 500 ± 350

Table II. — *Experimental values of the stopping power of copper, nickel and aluminium for* $^{18}O^{+}$ *ions implanted in* ⟨ 110 ⟩ *and* ⟨ 100 ⟩ *channelling directions. The energies of the incoming ions have been chosen in the investigated range and vary from* 11.5 *to* 37.5 keV.

	$-(dE/dx)/eV.Å^{-1}$				
	Cu		Al		Ni
E_0/keV	⟨ 110 ⟩	⟨ 100 ⟩	⟨ 110 ⟩	⟨ 100 ⟩	⟨ 110 ⟩
—	—	—	—	—	—
37.5	13.9 ± 0.8	15.5 ± 1	6 ± 0.6	8.5 ± 0.8	18.4 ± 1.5
27.5	12 ± 0.7	13.3 ± 0.8	5.1 ± 0.5	7.3 ± 0.7	15.7 ± 1.3
17	9.4 ± 0.5	10.4 ± 0.6	4 ± 0.4	5.7 ± 0.5	12.4 ± 1
11.5	7.7 ± 0.4	8.6 ± 0.6	3.3 ± 0.3	4.7 ± 0.4	10.2 ± 0.9

For the same energy of the incident oxygen ions the maximum range is higher for the ⟨ 110 ⟩ direction of implantation than for the ⟨ 100 ⟩ direction of implantation and R_{max} increases when the targets are respectively nickel, copper and aluminium single crystals.

3.2 Relation between the maximum range R_{max} and the energy E_0 of the incident ions. — The experimental values of the maximum range have been plotted *versus* E_0^{1-p} for various values of the exponent p. The deviation from a linear relationship between R_{max} and E_0^{1-p} has been checked by a least square method, this calculation takes into account the accuracy of the measurements to weight the experimental points. The smallest deviation from linearity is obtained for a value of p equal to 0.5. This deviation is only a few percent and consequently is smaller than the experimental uncertainties for the measured values of R_{max}.

When the experimental uncertainties of the measured values are taken into account, it is possible to conclude that, in the energy range investigated, the maximum range of channelled ions is proportional to their initial velocity. Consequently the slowing down of the best channelled oxygen ions is due to electronic energy losses when the direction of motion is parallel to the ⟨ 110 ⟩ and ⟨ 100 ⟩ directions of Cu, Ni, Al single crystals.

3.3 Experimental values of the stopping power. — As there is a linear relationship between the experimental values of R_{max} and $E_0^{0.5}$ it is possible to use the relations (2) and (3) to calculate the electronic stopping power of Cu, Al, Ni for oxygen ions. The values of k are deduced (relation (3)) from the slope of the linear relationship between R_{max} and $E_0^{0.5}$, this determination is made for each channelling direction and each material.

The corresponding values of $-dE/dx$ given in table II have been calculated with relation (2) for the different energies investigated.

For a same energy the value of the stopping power in the ⟨ 110 ⟩ direction is higher for nickel than for copper and is much smaller for aluminium. On the other hand the stopping power of copper and aluminium increases when the direction of implantation is varied from ⟨ 110 ⟩ to ⟨ 100 ⟩.

4. **Discussion of the results.** — 4.1 Comparison with theoretical calculations. — The accuracy of the orientation of single crystals is theoretically (cf. paper I) sufficient to agree with the conditions of proper axial channelling. The stopping power values deduced from the maximum range measurements correspond to the slowing down of ions which have experienced the lowest energy losses.

For these conditions it is interesting to compare the experimental results with those calculated for ions which have travelled just in the middle of a ⟨ 110 ⟩ or a ⟨ 100 ⟩ channel.

Firsov [5] has calculated the relation giving the electronic energy loss $\Delta E(R_0)$ for a binary collision with an impact parameter equal to R_0, this result may be used to determine the stopping power for a channelling direction if R_0 is set equal to the channel size.

As copper, nickel and aluminium are face centred cubic metals there is one general relation per channelling direction expressing the stopping power as a function of the lattice parameter a.

For the ⟨ 110 ⟩ direction there are two different impact parameters $a/2$ and $a\sqrt{2}/4$ with two collisions of each type and a repeat distance equal to $a/\sqrt{2}$ (Fig. 2*a*). The ⟨ 100 ⟩ direction involves one impact parameter $a\sqrt{2}/4$ with two collisions of the same type and a repeat distance of $a/2$ (Fig. 2*b*). The numerical values of the impact parameters and the repeat distances corresponding to Ni, Cu, Al for the ⟨ 110 ⟩ and ⟨ 100 ⟩ directions are summarized in the table III.

The theoretical values of the stopping power for each channelling direction are given by the following relations :

$$\frac{dE}{dx} = \frac{2\,\Delta E(a/2) + 2\,\Delta E(a\sqrt{2}/4)}{a/\sqrt{2}} \quad \text{for } \langle 110 \rangle \qquad (4)$$

$$\frac{dE}{dx} = \frac{2\,\Delta E(a\sqrt{2}/4)}{a/2} \quad \text{for } \langle 100 \rangle . \qquad (5)$$

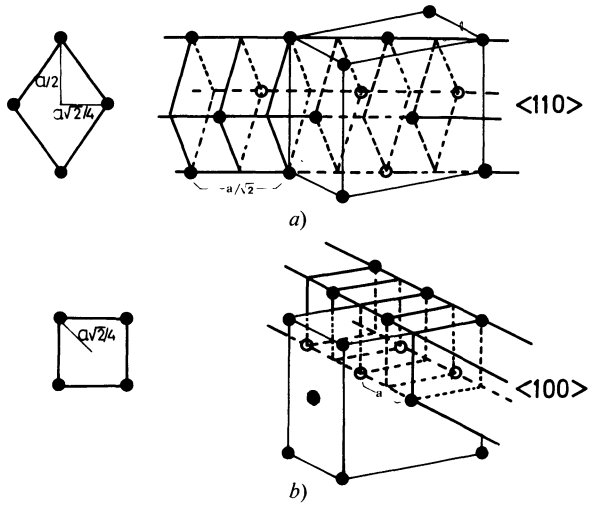

Fig. 2. — *a*) Schematic view of a channel parallel to a ⟨ 110 ⟩ direction in a face centred cubic crystal. The channel section has a diamond shape with two half diagonals equal to $a/2$ and $a\sqrt{2}/4$. *b*) Schematic view of a channel parallel to a ⟨ 100 ⟩ direction in a face centred cubic crystal, the section is a square with a half diagonal equal to $a\sqrt{2}/4$.

Table III. — *Numerical values of the impact parameters* (R_0) *and repeat distances* (λ) *corresponding to* Al, Cu, Ni. *These are used to calculate the theoretical channelling stopping power with Firsov's relation.*

			Aluminium	Copper	Nickel
⟨ 110 ⟩	R_0/Å	$a/2$	2.025	1.81	1.76
		$a\sqrt{2}/4$	1.43	1.28	1.24
	λ/Å	$a\sqrt{2}/2$	2.86	2.55	2.49
⟨ 100 ⟩	R_0/Å	$a\sqrt{2}/4$	1.43	1.28	
	λ/Å	$a/2$	2.025	1.81	

Numerical values of the theoretical stopping power of nickel, copper and aluminium have been calculated with relations (4) and (5), by expressing the energy loss ΔE with Firsov's relation. These values are compared to experimental results in the tables IV and V and we observe that they have the same order of magnitude but are higher of 20 % for Al ⟨ 110 ⟩ and Cu ⟨ 110 ⟩ and 15 % for Cu ⟨ 100 ⟩. If we take into account the experimental uncertainties they are in good agreement for Al ⟨ 100 ⟩ and Ni ⟨ 110 ⟩.

Table V. — *Stopping power of nickel for oxygen ions channelled along a* ⟨ 110 ⟩ *direction. Experimental values are deduced from* R_{max} *measurements and theoretical values are calculated with Firsov's relation.* E_0 *and* v *are respectively the energy and the velocity of the incoming* $^{18}O^+$ *ions.*

		Nickel $-(dE/dx)$/eV.Å^{-1} ⟨ 110 ⟩	
E_0/keV	v/cm.s^{-1} × 10^8	Experimental	Theoretical
37.5	0.63	18.4 ± 1.5	19.2
27.5	0.54	15.7 ± 1.3	16.5
17	0.43	12.4 ± 1	13
11.5	0.35	10.2 ± 0.9	10.7

The theoretical calculations give a variation of the stopping power depending on the channelling directions which is not as important as that observed experimentally for copper and especially for aluminium.

Firsov's relation has some limitations because of the Thomas Fermi model used to calculate the electron density. It would be interesting to calculate

Table IV. — *Stopping power of aluminium and copper for channelled oxygen ions. The experimental values are deduced from maximum ranges measurements and the theoretical values are calculated with Firsov's relation applied to channelled trajectories of* $^{18}O^+$ *ions.* E_0 *and* v *are respectively the energies and the velocities of the incoming oxygen ions.*

		Aluminium		Copper	
		$-(dE/dx)$/eV.Å^{-1} ⟨ 110 ⟩			
E_0/keV	v/cm.s^{-1} × 10^8	Experimental	Theoretical	Experimental	Theoretical
37.5	0.63	6 ± 0.6	7.6	13.9 ± 0.8	17.7
27.5	0.54	5.1 ± 0.5	6.5	12 ± 0.7	14.9
17	0.43	4 ± 0.4	5.1	9.4 ± 0.5	11.75
11.5	0.35	3.3 ± 0.3	4.2	7.7 ± 0.4	9.7
		$-(dE/dx)$/eV.Å^{-1} ⟨ 100 ⟩			
E_0/keV	v/cm.s^{-1} × 10^8	Experimental	Theoretical	Experimental	Theoretical
37.5	0.63	8.5 ± 0.7	7.9	15.5 ± 1	18.2
27.5	0.54	7.3 ± 0.6	6.8	13.3 ± 0.8	15.6
17	0.43	5.7 ± 0.5	5.3	10.4 ± 0.6	12.3
11.5	0.35	4.7 ± 0.4	4.5	8.6 ± 0.5	10.1

the electronic stopping power with a more adequate electronic structure and a different theoretical approach for the slowing down such as that used to calculate the variation of the stopping power of gold for various incoming ions [11].

4.2 COMPARISON OF THE PRESENT RESULTS WITH OTHER EXPERIMENTAL DETERMINATIONS OF THE STOPPING POWER. — The experimental determinations of channelled stopping power have generally been performed with ions having a velocity (around 1.5×10^8 cm.s^{-1}) higher than those of our experiments (see tables IV and V). According to theoretical results [1, 6] it is possible to assume that the electronic stopping power varies linearly with $E_0^{0.5}$ when the velocity of oxygen ions is smaller than 8.8×10^8 cm.s^{-1}. In this velocity range it is possible to extrapolate the present results (cf. table VI) so as to compare with other experimental values.

Table VI. — *Values of the stopping power of* Cu, Ni, Al *for* $^{18}O^{+}$ *calculated for a velocity of the ions equal to* 1.5×10^8 cm.s^{-1}. *They have been extrapolated from the experimental results obtained for lower velocities* (table II) *by assuming a linear relationship between* dE/dx *and* v.

		Copper	Nickel	Aluminium
		—	—	—
$-$ (dE/dx)/eV.Å^{-1}	$\langle$ 110 $\rangle$	33 ± 2	43.5 ± 3.5	14.1 ± 1.4
	$\langle$ 100 $\rangle$	37 ± 2.2		20.1 ± 1.7

Bottiger and Bason [9] have measured the stopping power of gold for several ion species channelled along a $\langle$ 110 $\rangle$ direction. They observe an oscillatory behaviour of dE/dx *versus* the atomic numbers Z_1 of the different ions which have the same velocity (1.5×10^8 cm.s^{-1}). Firsov's relation does not predict such oscillations but gives a fairly good approximation of the average behaviour. Unfortunately they give no result dealing with oxygen ions, but by extrapolating their values for N ($Z_1 = 7$) and Ne ($Z_1 = 10$) it is possible to show that the stopping power of gold for oxygen ions ($Z_1 = 8$) should be lower than Firsov's value by about 30 % (42.2 eV.Å^{-1} for the theoretical value and about 30 eV ± 2.5 eV.Å^{-1} for the extrapolated value). As Firsov's values of the stopping power of gold and copper for $\langle$ 110 $\rangle$ direction are respectively 42.2 and 41.45 eV.Å^{-1} it is interesting to notice that the experimental values (extrapolated) are also comparable $\sim 30 \pm 2.5$ eV.Å^{-1} and 33 ± 2 (table VI).

Other experimental results dealing with the stopping power of tungsten [2] and silicon [7] are not very easy to compare because these materials do not have the same crystalline structure as copper, nickel and aluminium. Nevertheless it is interesting to notice that the stopping power of silicon for oxygen ions channelled along a $\langle$ 110 $\rangle$ direction is also close from the theoretical value calculated with Firsov's relation.

5. **Conclusion.** — The linear dependence between R_{max} and $E_0^{0.5}$ indicates that the slowing down of the best channelled oxygen ions is due to electronic energy losses even in the low energy range investigated (10-45 keV). This allows the experimental determination of the electronic stopping power of Cu, Al and Ni for the oxygen ions. The values of dE/dx depend strongly on the nature of the material and are much lower for Al than for Cu and Ni. Although the atomic number Z_2 of Ni is lower than Z_2 for copper the stopping power of Ni is higher. The relation between the stopping power and the atomic number of the target is not a regular increase of dE/dx *versus* Z_2.

The experimental values obtained for copper have been compared with some extrapolation to other experimental results [9] and the agreement is good.

From a theoretical point of view Firsov's relation applied to channelling stopping power for oxygen ions gives a good order of magnitude agreement for Cu, Ni and Al, this conclusion may also be extended to other experimental results [7, 9]. This theoretical estimation describes the variation of dE/dx *versus* Z_2 and also *versus* the direction of channelling. But accurate determination of the stopping power cannot be obtained with this theoretical approach because the Thomas Fermi model used by Firsov does not fit very well the electronic density in the channels. A better approximation could be obtained in calculating electron densities with Hartree-Fock wave functions. This modification of Firsov's model has already accounted successfully for the Z_1 oscillations of the stopping power of Si, W and Au [10, 11].

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