EFFECT OF ANNEALING ON THE LATTICE PARAMETER OF NEUTRON-IRRADIATED COPPER*

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Although annealing behavior of irradiated fcc metals has been investigated many times, the assignment of the different recovery stages observed to the migration and annihilation of various point defects is still a matter of discussion.[1] Most experimental information has been obtained from electrical resistivity measurements. Further insight can be expected by applying another method of investigation. E.g., point defects give rise to a distortion of the crystal lattice and to a change of the lattice parameter, which can be measured by the x-ray scattering method.[2,3]

In this paper we report about lattice-parameter measurements in neutron-irradiated copper. Pure copper single crystals (99.999%) were irradiated in the low-temperature irradiation facility of the Munich Research Reactor (Forschungs Reaktor Munich)[4,5] at 4.6°K. After irradiation the crystals were transferred without raising the temperature to a special helium cryostat for the x-ray measurements. The total experimental arrangement is improved in comparison with that used at earlier measurements.[6,7] The lattice parameter was obtained from the position of the (400) Co $K\alpha$ x-ray reflection. The lattice parameter was always determined at liquid-helium temperature. For isochronal annealing the crystal was warmed in steps to successively higher temperatures with an isochronal holding time of 10 min. Figure 1 shows the relative lattice parameter change $\Delta a/a$ measured at liquid-helium temperature as a function of the annealing temperature for two runs. For normalization the values are divided by the total change $\Delta a_0/a$. Annealing of the electrical resistivity change after neutron irradiation at the same position in the reactor is shown for comparison. After annealing at 670°K the radiation effect in resistivity and lattice parameter is completely annealed. The thermal annealing of lattice parameter and resistivity change proceeds in annealing stages lying in the same temperature regions, whereas the relative height of the stages is different for the two different properties. (See Fig. 1, Table I.) The following conclusions can be drawn:

(1) If resistivity and volume change are proportional to the defect concentration in neutron-irradiated copper, the ratio $(\Delta V/V)/\Delta Q$ is a specific defect property. The difference in the ratio shows that defects are annihilated in different stages which are different in specific resistivity change and/or volume change.

If interstitials in different configuration recombine with vacancies in stages I, II, and III, we can conclude that $Q_F{}^{I} < Q_F{}^{II,III}$ since calculations show that the volume change of different interstitial configurations is nearly the same (1.1, ···, 1.4 atomic volumes).[8] This would be in accordance with the assumption[1] that in stage I a different type of interstitial recombines with vacancies than in stages II and III. The value of $Q_F{}^{I} = 120, \cdots, 210$ $\mu\Omega$ cm/unit concentration is in agreement with others' and our experimental results.[9]

(2) The defect clusters annealing in stage V[10] give rise to different distortion fields and resistivities compared with single defects. The measurements show that in the cluster the distortion volume per defect is more strongly re-

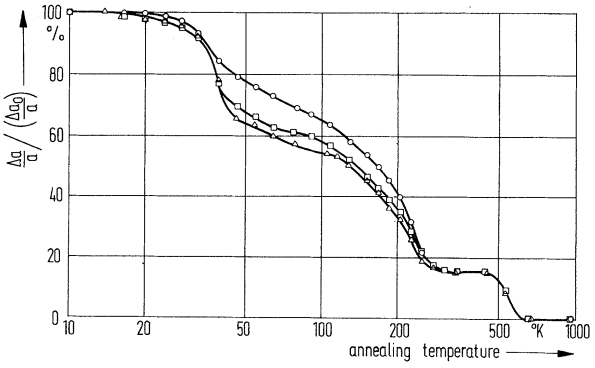

FIG. 1. Isochronal annealing of neutron-irradiated copper. Triangles, run I; squares, run II; circles, electrical resistivity (for data see Table I).

Table I. Summary of experimental results

Run	Irrad. time (h)	$\frac{\Delta a_0}{a} \times 10^4$	$\Delta\varrho_0$ ($n\Omega$cm)	Annealing range ($^\circ$K)	$\frac{\Delta a/a}{\Delta a_0/a}$ (%)	$\frac{\Delta\varrho}{\Delta\varrho_0}$ (%)	$\frac{3\Delta a/a}{\Delta\varrho_0}$ ($m\Omega^{-1}cm^{-1}$)
I	46.0	2.71±0.08	124±2[a]	4-60	38±5	31±2	8.0±2.0
				60-300	46±5	51±2	5.9±1.0
				300-1,200	16±5	18±1	5.8±1.6
II	86.3	3.75±0.15	190±2[b]	4-60	36±5	29±1.5	7.4±1.5
				60-300	48±5	54±1.5	5.2±0.6
				300-1,200	16±5	17±0.5	5.6±1.6

[a]From measurements in the same irradiation position

[b]Measured simultaneously with a different sample at the same irradiation position

duced than the resistivity per defect per atom compared with the single-defect values.

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TEMPERATURE DEPENDENCE OF ULTRASONIC PARAMAGNETIC RESONANCE IN MgO:Fe^{2+} †

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The technique of ultrasonic paramagnetic resonance (UPR) provides a particularly direct means of investigating electron-spin–phonon interactions.[1,2] Because most UPR measurements have been made at 10 GHz, at which frequency the background acoustic attenuation rises rapidly above 4°K, they have been restricted to liquid-helium temperatures. At lower microwave frequencies, at which the acoustic attenuation permits measurement over a wider range of temperature, the pulse techniques[1,2] most often used are not sensitive enough to observe UPR in most paramagnetic ions.

In this paper we report measurements of the UPR of Fe^{++} ions in MgO at 1.1 GHz over a temperature range of 4.2 to 30°K. Measurements were made on the temperature dependence of the amplitude of both the absorption and dispersion signals and on the temperature dependence of the linewidth. To our knowledge these are the first reported measurements of either UPR absorption or dispersion over an extended temperature range. The measurements were made using a sensitive continuous wave (cw) ultrasonic technique which involves exciting a mechanical resonance in the sample.[3] Ultrasonic absorption decreases the Q of the mechanical resonance line while ultra-