cal values.[3]

On the contrary, ultrasonic attenuation experiments at low temperatures never succeed in reaching that relaxation time because of the stronger impurity effect. It is here that the usefulness of the method of boson echoes enhances the possibility of studying inelastic scattering in the low-temperature regime.

In this Letter, some simplifications have been made. In fact, there are two kinds of echoes: (i) Those for which the radiated electromagnetic field is proportional to ϵ^2 (where ϵ is the strain). We call them quadrupolar elastic echoes; detailed calculations show that all the echoes (at times 2τ, $2T$, $2T-\tau$, and $T+\tau$) have a quadrupolar contribution. (ii) The others for which the radiated electromagnetic field is proportional to ϵ. We call these dipolar elastic echoes; they give no contribution to the echo at $T+\tau$.

Besides these results, other effects take place at high power levels of the pulses. Saturation of the echoes appears first, and when power is further increased, nonlinear interactions between the phonons themselves generate new echoes whose origin has been explained by Herrmann, Kaplan, and Hill[4] in the case of magnetoelastic modes.

In conclusion we must emphasize first the simplicity of this method, especially when it is compared with the ultrasonic method which requires a careful preparation of the samples; however, it depends on the absence of a center of symmetry for the crystal studied. Second, the fact that T_1 may be as large as 0.1 sec at 4°K indicates that the phonon population has a Q factor of the order of 10^9. Thus the phonon echoes may become a very powerful tool for studying weak inelastic interactions in crystals.

Detailed calculations and more information on the numerical results will be published elsewhere.

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Giant Electron Spin-Resonance Transmission in Cu Ion Implanted with Mn†

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We observed for the first time the transmission of electron spin resonance through a thin copper foil implanted with Mn on either one or both sides at a dose of about 10^{15} ion/cm^2. We found an increase of intensity over that of the pure metal, at 1.5°K, by a factor of 50 for one-sided–implanted samples and 2500 for two-sided–implanted samples. This enhancement decreases with increasing temperature, while the g factor remains very close to that of pure copper metal.

We wish to present here a set of new observations concerning the transmission of conduction-electron spin resonance (CESR) through a Mn-implanted thin slab of a single crystal of copper. Although we do not at the present time have a satisfactory theoretical or phenomenological model to account for all the features of the observed resonances, we believe that our results are sufficiently striking to be presented as such without detailed analysis of their microscopic meaning.

Conduction-electron spin resonance in dilute alloys so far has been studied in situations where the concentration of the alloy was homogeneous over the whole sample. In that case it is possible to analyze the results in terms of the same formalism as for a pure metal[1,2] by properly rewriting the ESR parameters in terms of impurity and host intrinsic properties.[3,4]

In the present case, however, we shall deal with a situation completely opposite where a slab of pure copper is doped over a small distance with a high concentration of magnetic impurities. One can then think of the impurity layer as an efficient means to couple the electromagnetic radiation outside to the conduction-electron spins inside the pure metal via their spin-spin interaction. This simple view is supported so far by the present set of observations which show that the enhancement of ESR transmission in a sample implanted on *both* sides is about *the square* of the enhancement found if only one side is implanted. This enhancement factor reaches 2500 at 1.5°K for a dose of 5.2×10^{14} Mn/cm^2 implanted ions on each side. If further work on this system proves the correctness of this idea, this method could become a powerful tool of observation of electron spins in metals.

Before presenting our results, we very briefly recall our geometry of observation for ESR and give the sample preparation conditions: Transmission ESR[5-8] on copper is made by clamping a thin (typically 40-μm) foil of pure copper to form a common wall between two well-isolated resonant microwave cavities tuned to the same frequency. Into one of them, called the emitter, a constant microwave power is fed, while the other (receiver) is coupled to a sensitive detector (10^{-18} W typical). The conduction electrons diffuse from one face to the other inside the foil and can carry over a small amount of power with their spins when the Larmor conditions for ESR is fulfilled. The geometry of the cavities in our case is identical with that used by Schultz and co-workers[4] and allows arbitrary orientation of the magnetic field with respect to the sample. For samples implanted on one side only, one can choose to place the implanted side towards the emitter or receiver cavity. The change to the opposite choice can be made by suitably crossing the wave guides outside so that the cavities exchange their roles. From the copper metal[9] taken as a starting material, a single crystal is grown which is appropriately cut and polished to yield thin (40 μm) strainless slices[4,6] of random orientation. Ion implantation is achieved using an ion isotope separator equipped with post-acceleration so that the total energy was 110 keV for unit charge. As Mn^{++} was selected the energy was 220 keV; so the corresponding penetration depth in copper is ~600 Å.[10] The width of the Mn distribution appears to be about twice this

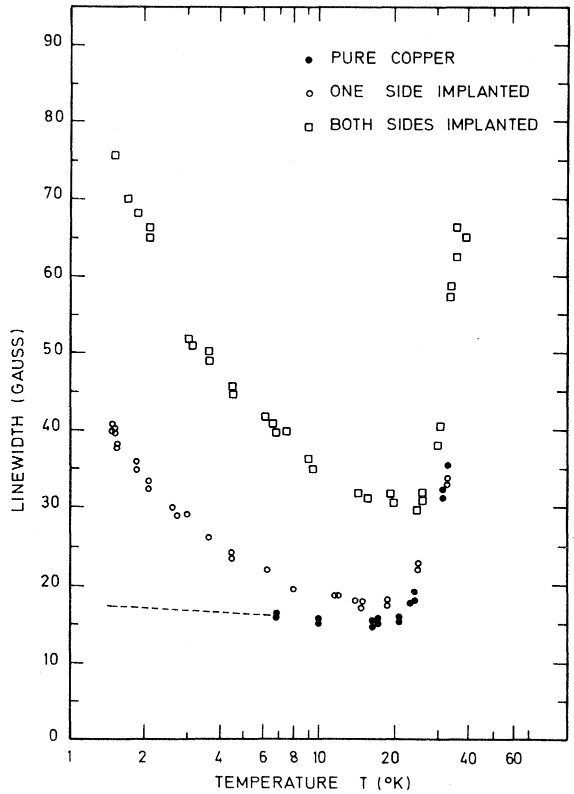

FIG. 1. ESR linewidth versus temperature for pure copper and for one-sided and two-sided Mn-implanted samples.

mean depth from a direct observation using a secondary-ion microanalyzer.[11] One can then speak of an average concentration of implanted Mn by dividing the dose/cm^2 by this width. This turns out to be about 1000 ppm at. Mn/at. Cu for a dose of 5.2×10^{14} implanted ions.[12] It should be recalled that the skin depth in a homogeneous alloy of 1000 ppm at 10 GHz is ~3500 Å, thus all the Mn ions will see directly this microwave field. The samples *have not been annealed*, in contrast to similar work done on semiconductors,[13] and no attention has been given to channeling or crystal orientation.

(a) *Pure copper.*—Our reference ESR is that of our starting copper material.[9] We find the same behavior of the resonance as mentioned in Ref. 6 with a limiting linewidth of about 16 G at low temperatures as shown in Fig. 1. We define the intensity of the signal as the product of the width ΔH (at half-maximum) by the maximum amplitude A as shown in the inset of Fig. 2, normalized to a given power of incident microwaves, a given gain, and a given sample thickness.[14] This intensity is approximately temperature indepen-

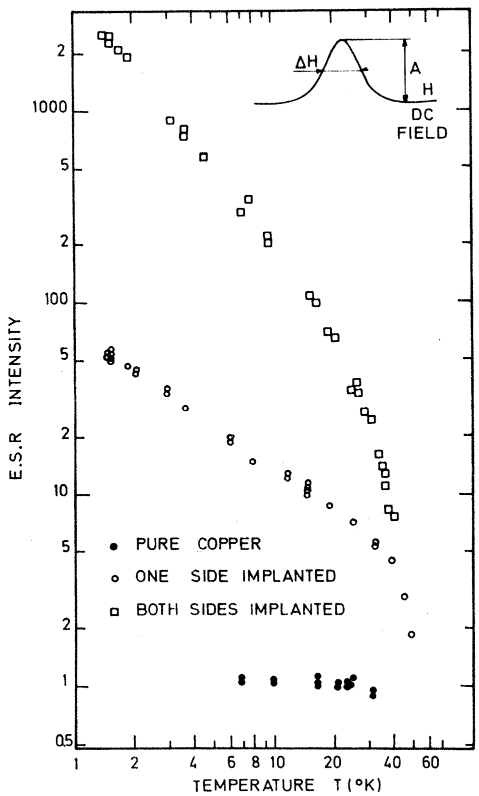

FIG. 2. Intensity of ESR signal versus temperature for pure copper and for one-sided and two-sided-Mn-implanted samples.

dent for pure copper below 30°K as shown in Fig. 2, but drops sharply above that temperature as the spin diffusion length becomes shorter than the sample thickness because of scattering by the phonons. The g factor is found to be 2.033 ± 0.002 using an NMR calibration of the field which is itself compared with the ESR of metallic Li.[4,6] As usual, much stronger signals due to the coupling of the charge of the electron to the rf electric field form a background at low temperatures.[15]

(b) *One-sided implantation.*—The transmitted ESR in this case appears very similar to a pure metal one; in particular, the strong electrical signals still appear in the background indicating a pure bulk metal propagation.[6] The line shape of the spin signal is Lorentzian-like and can be adjusted to be symmetric. As shown in Fig. 2 the intensity, defined to be unity for pure copper, is about 52 at 1.5°K.[16] Furthermore, the intensity is strongly temperature dependent: It decreases to about 5 at 40°K and then falls off more rapidly. The line shape remains Lorentzian-like until ~40°K like the pure metal.[6] The linewidth at half-maximum up to this temperature is measured and plotted in Fig. 1. It appears that, in contrast to the homogeneous CuMn alloys,[4] the linewidth *decreases* with increasing temperature from 40 G at 1.5°K to a value slightly above that of pure copper at 20°K. The g factor for a symmetric signal is consistent with that of pure copper. Within the precision of measurement, it does not seem to vary with temperature and is found to be $g = 2.032 \pm 0.003$. It is nowhere near the intrinsic g value of Mn in Cu as determined by many authors.[17] Two questions immediately arise: (1) What happens when the roles of the cavities are exchanged? (2) What is the amplitude and shape, compared to the pure metal, of the signals of electrical origin, responsible for the background?

The answer to the first point is that the transmitted spin and background signals remain *unchanged* with permutation of cavities for a one-sided implanted sample. Preliminary estimates indicate the background signals to be enhanced also (but less than the CESR) by a factor of 5 for the one-sided implantation and by about 12 for the two-sided implantation. However, the shape of these signals is unaffected as checked after etching away the implanted layer of copper.

(c) *Double-sided implantation.*—The main question before doing this experiment was whether this enhancement factor would be additive or multiplicative upon implanting the two sides. The answer is very clearly given in Fig. 2[18]: The intensity is now multiplied by a factor of ~50 × 50 = 2500 above the bare copper signal and decreases faster with temperature. The linewidth behavior is represented in Fig. 1. The effect of the second implantation is to increase the low-temperature width from 40 to 75 G. The linewidth also decreases with increasing temperature, but reaches a value near 20°K markedly greater than that of pure copper.[19] One of the most striking phenomena is that the g factor seems to be completely unaffected; it remains independent of temperature at a value close to that of copper (2.032 ± 0.003). Like the one-sided implantation results, all these parameters are independent of the orientation of the magnetic field with respect to the sample.

The possibility of observing ESR on Cu implanted with Mn shows, first of all, that although it is estimated[20] that about 1000 lattice atoms are displaced by each incoming ion, the defects created are either ineffective for spin scattering or self-annealing at room temperature. The multiplicative enhancement effect is further proven by plotting the logarithm of intensity of two-sided implanted ESR versus the logarithm of the signal of the one-sided–implanted sample: This exhibits a slope of 1.9 ± 0.15. Rather than trying to guess what is the common answer to these observations, we summarize briefly the features that we think have to be explained by a theoretical model: (1) Transmitted ESR for samples implanted on one side is independent of which side is excited by the microwaves. (2) ESR intensity is enhanced by a large factor which is squared for double-sided implantation. (3) The g factor is characteristic of copper metal. (4) The intensity, as well as the linewidth, decreases with increasing temperature at low temperatures. (5) The diffusion coefficient D seems to remain close to that of copper, as evidenced by the high-temperature falloff of the signal. (6) ESR is independent of magnetic-field orientation on the sample. (7) The background electrical signals are also enhanced, but to a lesser extent than the spin ones.

A large number of situations can be studied in this system. Among the most promising ones are the possibility of exploring ESR of a large number of metals hitherto not pure enough for ESR studies; the possibility of exciting spin modes other than CESR because of the high gradients of magnetization probably present near the surface[19]; and the possibility of studying implantation defects.

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