Abstract

A simple model is used to analyse published results on large room-temperature diamagnetism for two films of oxidised atactic polypropylene (OAPP) at low magnetic fields. The model involves induced currents expected in circular closed loops of superconductors in fields below the lower critical field $H_{c1}$ at which flux penetration would first occur if a metamagnetic transition did not intervene as in OAPP, and the assumption that resistance would be restored at $H_{c1}$ (negligible pinning). Fits to the data for the more strongly magnetic sample with the model, allowing two different types of loops with different radii $b_1$ and $b_2$, but with the same cross section $a$ of loop material yield $H_{c1} \approx 5260$ Oe, and fits to the data for the less strongly magnetic sample with two loop sizes and with the same value of $H_{c1}$, combined with the knowledge that the minimum number of closed loops of any type is one, requires that the radius $a$ of the cross section of the material should be less than about 0.8 $\mu$m, in fair agreement with a maximum radius of 1 $\mu$m obtained previously from other data.

Keywords: Room-temperature superconductivity, Oxidised atactic polypropylene, Magnetization, Lower critical field $H_{c1}$.

1. INTRODUCTION

There is evidence from at least three different types of experiments that narrow channels through films of oxidised atactic polypropylene (OAPP) are superconducting at room temperature. The three types of evidence are (i) lower limits for conductivity several orders of magnitude greater than that of copper, found by direct \cite{1} and indirect \cite{2} methods, (ii) non-thermal destruction of ultra-high conductivity by high pulsed currents, with critical current densities greater than $10^9$ A cm$^{-2}$ \cite{2}, and (iii) negligible electronic contribution to the thermal conductivity \cite{3}. Further support for high-temperature superconductivity in channels of a different polymer is that the thermopower between 87 and 233 K in films of poly(octylmethacrylate) is zero to within estimated errors of measurements \cite{4}.

The magnetic properties of films of OAPP are also unusual. The unusual properties observed in samples in which highly conducting channels occur are (i) a metamagnetic transition in fields of a few kiloeirsted \cite{5-7}, (ii) large diamagnetism observed at low fields in about 10%
of the samples showing a metamagnetic transition [6,7], and (iii) spontaneous forces occurring in some field range tending to push samples to lower magnetic field regions in inhomogeneous magnetic fields [8].

At least three different models have been suggested for the ultra-high conductivity or the superconductivity [9-14], two for the high critical current densities in channels [10-14], and two for the unusual magnetic properties [6,7,11,12]. Authors of papers on both types of models for the magnetic properties are agreed that the large diamagnetism in some samples and the occasional spontaneous forces pushing samples out to low-field regions in inhomogeneous fields are associated with superconducting channels which form closed loops, but differ as to what is happening in these closed loops. In [11,12] I suggested that large spontaneous currents occur when closed loops form, and gave support for this hypothesis on the basis that some data in a figure in [15] appear to show that the susceptibility is approximately proportional to (1/field), indicating a constant moment, independent of field, whereas the authors of [7] appear to think the large diamagnetism (of the order of a percent of a complete Meissner effect at low fields in one sample) is associated with the percentage of the film which is superconducting. We think that this hypothesis is not compatible with the assumption that the diamagnetism is associated with closed loops, since the total fraction of material occupied by conducting channels is typically at most a few percent (channels separated by 7-8 µm estimated in one very thin film, thickness 0.3 µm, showing conducting channels [16], and channel diameters always less than 2 µm [17,2]), the fraction of material in closed loops can be expected to be considerably less than this, and also the Meissner effect may be further reduced if the magnetic-field penetration depth is comparable to channel radii. However, recent experimental results [7] do not appear to support the spontaneous moment hypothesis well either, as there is at best only a small range of fields for which the diamagnetic moment is approximately constant.

In this paper we explore the hypothesis that the diamagnetic moment is associated with induced supercurrents at fields below which the loop becomes resistant. We make use of a theory for induced currents in circular loops of Type I superconductors below the critical field, discussed in Shoenberg’s book (1952 version) [18]. Looking at the derivation of his results, it appears that they will apply to Type II superconductors below $H_{c1}$ if there is negligible flux line pinning, so that resistance is restored as soon as fields reach $H_{c1}$. A metamagnetic transition may occur before $H_{c1}$ is reached, but we assume that the metamagnetic transition, being a cooperative phenomenon, will not occur until the average field throughout the material of the loop reaches a certain value $H_M$, and so supercurrents can continue to flow even if the field near the outer surface of the loop is greater than $H_M$, provided that the average field in the material is smaller than this value.

Since only a small fraction of the conducting channels form closed loops, we assume that the observed diamagnetism at low fields is a superposition of a diamagnetism associated with closed loops, and a smaller positive magnetisation as found by a combination of results of observations made on the next day after closed loops have been destroyed by large fields and extrapolation. Thus we fit the larger diamagnetism found after correcting for this effect.

2. FITTING DATA WITH TWO TYPES OF SUPERCONDUCTING LOOPS

Let us introduce the notation $H_R$ for the field at which resistance appears in the superconducting channels of which the loops are made, either $H_c$ for a Type I superconductor, or $H_{c1}$ for a Type II superconductor with no pinning. Let us define a field

$$H_B = 0.5H_R.$$  

Then Shoenberg’s type of theory [18] shows that, for a circular loop of superconductor of radius $b$ with a circular cross section of material of radius $a$, initially in zero field, the magnetisation
commences to vary linearly with applied field $H_e$ perpendicular to the plane of the loop to a value

\[ m_A = -\frac{\pi ab^2 H_B}{1 + La/\pi b^2} \]  

when the field reaches a value $H_A$ given by

\[ H_A = H_B \frac{La/\pi b^2}{1 + La/\pi b^2}, \]

where $L$ is the inductance of the loop. The inductance is given by

\[ L = 4\pi b X, \]

where, for supercurrents confined to the surface of the material of the loop,

\[ X = [\ln(8b/a) - 2], \]

whereas for supercurrents through the bulk of the material of the loop,

\[ X = [\ln(8b/a) - 7/4]. \]

For, e.g. $b/a = 50$, the difference in the two values of $X$ is 6%. For definiteness we shall do our calculations with the first value of $X$, which will be correct if the magnetic-field penetration depth is small compared with $a$. The initial susceptibility $\chi$ associated with the loop is

\[ \chi = -\frac{\pi b^3}{4X}. \]

As the applied field is increased above $H_A$, the magnitude of the magnetic moment decreases linearly with field until the field $H_B$ is reached, at which field the magnetic moment is

\[ m_B = -\pi ba^2 H_B. \]

At fields above $H_B$, ignoring a small discontinuity in moment at $H_B$ mentioned by Shoenberg but not discussed in detail, there is a linear decrease of the magnitude of the magnetic moment from the value given by Eq. (7) to zero at a field approximately equal [to lowest order in $(a/4b)$] to $2H_B = H_R$.

In order to fit the observed moments starting from zero applied field and continuing up to the field at which the metamagnetic transition occurs for the sample of [7] with the largest moment, we use a model with two types of loops with different $b/a$ ratios,

\[ r_1 = b_1/a > b_2/a = r_2, \]

with $a$ the same for both loop types, and suppose that there are $N_1$ and $N_2$ loops of each type. Such a model is used as a first approximation to a model with a semicontinuous distribution of loop parameters. We also assume that the planes of the loops are parallel to the film surfaces, i.e. perpendicular to the applied field. For the larger loops, geometrical constraints for a film of thickness 10 µm [7] force any closed loops to have approximately this orientation. If some of the smaller loops have other orientations, then probably the theory will still hold approximately with the reinterpretation of loop areas as the average projections of their areas on to planes parallel to the film surfaces.

The model with two types of loop parameters has four straight-line segments on the moment versus field curve, with discontinuities in slope at fields $H_{A1}, H_{A2},$ and $H_B$, where $H_{A1}$
and $H_{A2}$ are given by Eq. (3) for the two different values of $b/a$. The magnetic moments at the points of discontinuity of slope are given by

$$m(H_{A1}) = N_1 m_{A1} + N_2 m_{A2}(H_{A1}/H_{A2}),$$

(10)

$$m(H_{A2}) = N_1 m_{A1} - N_1 (m_{A1} - m_{B1})(H_{A2} - H_{A1})/H_{B} + N_2 m_{A2},$$

(11)

$$m(H_{B}) = N_1 m_{B1} + N_2 m_{B2},$$

(12)

with the magnetisation going to zero at $H_R = 2H_B$. In Eqs. (10) to (12), the second suffices 1 and 2 on $m_A$ and $m_B$ refer to the two types of loops.

After correcting for a probable effect of superposition of diamagnetism associated with closed loops with a smaller positive moment associated with the majority of conducting channels which do not form closed loops, as discussed in the introduction, we fit the data for the more strongly magnetised sample with five adjustable parameters, viz. ($b_1/a$, $b_2/a$) (assuming $b_1 > b_2$), $N_1 m_{A1}$, $N_2 m_{A2}$, and $H_B$. We find that $b_1/a = 133$, $b_2/a = 7.9$, $H_B = 2631$ Oe, implying $H_{A1} = 5262$ Oe, and, with use of the fact that the volume of the film $10^{-3}$ cm$^3$ [7], that $N_1 m_{A1} = -1.69 \times 10^{-4}$ emu, and $N_2 m_{A2} = -1.25 \times 10^{-4}$ emu. Using Eqs. (2), (4) and (5) we deduce that $N_2/N_1 \approx 380$, corresponding to a ratio of area covered by the smaller loops to that covered by the larger loops of about 1.3. We used a program AMOEBA given in a book [19] to perform the least squares fitting. The fit to the data up to the field of about 1390 Oe is shown in Fig. 1. The rms accuracy of the fit is 2.2% of the mean value of the inferred diamagnetism, or 3.3% of the mean value of the net observed magnetisation.

For the second sample we assume that the corrections for a positive moment from the channels which do not form closed loops have values half of those for the first sample, based on the estimate in [7] that the average electron concentration in the second sample is about half that of the first sample. We use the same type of model with two different values of $(b_1/a)$, but keep $H_B$ as before, and so we have a four-parameter fit. We find $b_1/a = 106$, $b_2/a = 14.4$, and, with the volume of the film as $10^{-3}$ cm$^3$ [7], $N_1 m_{A1} = -0.35 \times 10^{-4}$ emu, $N_2 m_{A2} = -0.25 \times 10^{-4}$ emu. From Eqs. (2), (4) and (5) we deduce that $N_2/N_1 \approx 58$, corresponding to a ratio of the area covered by the smaller loops to that covered by the larger loops of about 1.1. The rms accuracy of the fit is 2.4% of the mean value of the inferred diamagnetism, or 6.3% of mean value of the net observed magnetisation. The fit to the data up to the field of about 1390 Oe for the metamagnetic transition for this sample is also shown in Fig. 1. Since $N_1$ cannot be less than 1, we deduce from Eqs. (2), (4) and (5) and the value of $N_1 m_{A1}$ that the radius $a$ of the cross sections of the channels forming the loops is less than 0.76 $\mu$m. This is in fair agreement with an upper limit of 1 $\mu$m estimated from other data [17,2]. A lower limit for channel radii of 0.1 $\mu$m is estimated in [20], and a stricter upper limit of 0.35 $\mu$m is mentioned in [2], but with only a reference to a future publication (which has not appeared yet as far as I know) for an explanation of how this limit is obtained.

From the parameters obtained we find that the fraction of the first sample occupied by the material of the closed loops is $7.9 \times 10^{-5}$ for the set of smaller loops and $0.35 \times 10^{-5}$ for the set of larger loops, independent of the value of $a$. The total is sufficiently small compared with the probable total fractional volume of the order of a percent occupied by all conducting channels that we are justified in using approximately the same correction for positive magnetisation as that for all channels after the closed loops are broken, inferred from magnetisation measurements on the day after the original measurements [7]. The contributions to the initial susceptibility from the larger and smaller loops are $-4.9 \times 10^{-4}$ emu cm$^{-3}$ and $-0.9 \times 10^{-4}$ emu cm$^{-3}$ respectively,
corresponding to a total of 0.7% of that for a complete Meissner effect. The appreciably smaller fraction of superconducting material compared with the fraction of the full Meissner effect for the initial susceptibility arises because the susceptibility due to induced currents for a closed loop is larger by a factor of \((1/2X)(b/a)^2\) than that due to a Meissner effect keeping the flux completely out of the material of the loop. Although, for the model used, most of the material of the superconducting loops is associated with the smaller loops, the dominant contribution to the initial susceptibility comes from the larger loops because of the factor \((b/a)^2\).

For \(a = 0.76\mu m\), the maximum induced currents in the loops, at the fields \(H_{Ai}\) \((i=1,2)\), vary between 1.0 A and 1.7 A, depending on the loop size. These currents are considerably smaller than the critical currents of about 60 A through films in pulsed measurements with microprobe contacts of diameter 10 \(\mu m\) on the top surface of the films [2]. Probably there was contact with only one conducting channel in these measurements, but in any case there could not have been many channels involved. We presume that the reason for the larger critical currents in the pulsed measurements is that any magnetic flux associated with the current does not have time to enter the channel, and so critical currents in this case are determined by other factors, and may equal depairing currents.

3. DISCUSSION

The use of two different values of \((b/a)\) is a simplification of a model with a quasi continuous distribution of \((b/a)\)'s. With a quasi continuous distribution, rounding out of corners of the magnetisation curves would occur.

Since a transition temperature greater than room temperature is very high for a superconductor, we expect a small coherence length and Type II superconductivity. Also, because of the high temperature and softness of the material, pinning of flux may be difficult. Thus our model may be appropriate. A value of about 5260 Oe is inferred from the data for the lower critical field \(H_{c1}\) which would exist for fields perpendicular to the superconducting channels if a metamagnetic transition did not intervene at a lower field. At 4.2 K, high conductivity does not disappear for fields up to 9 tesla [21] (probably approximately parallel to the channel lengths), and so \(H_{c2}\) at this temperature for some orientation of the field is greater than 9 T. Since \(T_c\) has been estimated indirectly to be greater than 700 K in [2], the low-temperature critical fields may be close to those at room temperature. For the high-temperature oxide superconductor YBa\(_2\)Cu\(_3\)O\(_7\), \(H_{c1}\) for fields perpendicular to the film planes is about 700 Oe at low \(T\) [22]. It would not be surprising to find much higher values of \(H_{c1}\) in oxidised atactic polypropylene in view of the much higher \(T_c\).

We have ignored interaction between current loops, and between current loops and the larger amount of positively magnetised material in channels not forming closed loops. Such interactions can on average be taken into account by demagnetisation fields. Since the maximum susceptibility is always below 1% of that corresponding to a full Meissner effect, such corrections can be expected to be represented by changes in the internal field with respect to the applied field by amounts equal to a fraction of a percent of the applied field.

We know of no non-superconducting material which can show diamagnetism as large as a few tenths of a percent of a full Meissner effect. For fields along the \(c\)-axis, graphite has a susceptibility of \(21.1 \times 10^{-6}\) emu g\(^{-1}\) [23], which corresponds to 0.06 % of a complete Meissner effect, about an order of magnitude smaller than the initial susceptibility for the more magnetic of the two films discussed here.

Although ballistic transport of electrons in arrays of small current loops may give some magnetic properties similar to those of superconductors [24], the characteristic temperature \(T^*\)
below which ballistic effects occur for a loop with $N$ electrons and radius $R$ is [24]

$$k_B T^* \sim \frac{\hbar^2 N}{2mR^2},$$  \hspace{1cm} (13)

with $m$ the electron mass. Taking $N \sim R/a_0$, where $a_0$ is the period of an assumed periodic system, this reduces to $k_B T^* \sim (\hbar^2/2m)(1/a_0 R)$. Assuming e.g $R = 1\mu m$ and $a_0 = 0.5$ nm, we find $T^* \sim 0.9$ K. To move $T^*$ up to room temperature, we would thus need to reduce $R$ to $3$ nm, which would imply a radius of the material of the loop of $\sim 1$ nm or less. Although we could obtain an initial diamagnetic susceptibility as high as 0.7% of a Meissner effect by postulating very large numbers of such tiny loops and using Eq.(7), such small sizes would be incompatible with what is known about conducting channels through the films, which have cross sections with radii of the order of $1.0 \mu m$ [2]. Thus it appears that an interpretation of the diamagnetism in terms of ballistic effects in mesoscopic systems at room temperature is very unlikely.

While our model for the diamagnetism associated with superconducting loops has several arbitrary parameters, and may not be the only type of superconductor model which can explain the diamagnetism, we have shown that a plausible model to interpret the diamagnetic properties can be found based on concepts similar to those used to explain the strong evidence for superconductivity in channels from the three types non-magnetic experiments mentioned at the beginning of the paper.

One way to test the model discussed here would be to cycle the magnetic field in a suitable sample, keeping within a field range below that at which the metamagnetic transition occurs, and to compare the predictions for the complete cycle with Shoenberg’s theory [18]. However, since only about 10% of the samples with conducting channels are reported to show large diamagnetism [6], finding a suitable film for such measurements may not be easy. The only recent reports of work on oxidised atactic polypropylene come from Professor Grigorov and members or ex members of his group, several of whom are now working for commercial companies in the USA, and from Shlimak and Martchenkov [25], of Bar-Ilan University, who have done more work on polydimethylsiloxane (PDMS), (which also shows some of the unusual properties found in OAPP [20,26]), but also some on oxidised atactic polypropylene. Besides having some room-temperature properties similar to those of OAPP, the Josephson effect has been observed for PDMS sandwiched between two superconductors at temperatures below $T_c$ of the superconducting contacts [27].

Another type of polymer which shows narrow channels through films with fairly high conductivity is poly(3,3'-phthalidylene-4,4-biphenylylene) (PPB) (see e.g. [28]). Although no suggestions that these channels are superconducting at high temperature have been published, resistance too low to be detected has been found through PPB films with Sn contacts at low temperatures [29]. Josephson effects have been reported in polyimide [30]. Further studies of both these materials, especially of magnetic properties, may be worthwhile.

Two other examples of what may be quasi one-dimensional systems with superconductivity at room temperature are (i) carbon deposits containing multiwalled nanotubes [31-33], and (ii) powdered mixtures of PbCO$_3$.2PbO + Ag$_2$O [34]. The structure of the superconducting components of the system studied in [34] has been suggested to contain well separated Ag-O chains which are thought to be the main channels for possible superconductivity in this system.

4. CONCLUSIONS

Fair fits to the magnetisation curves showing large diamagnetism at low fields at room temperature in two samples of films of oxidised atactic polypropylene have been obtained using a model involving superconducting current loops in applied magnetic fields below those at which metamagnetic transitions occur, and also below the field $H_{c1}$ at which resistance would appear
assuming no pinning if a metamagnetic transition did not set in first. Two sizes of loops with the same radius \(a\) of the cross section of the superconducting channels of the loops are assumed. For the second sample, \(a\) has been estimated from the fit to be less than about 0.8 µm, in fair agreement with \(a < 1\mu m\) estimated from other data [2,17].

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REFERENCES

1. V.M. Arkhangorodski, A.N. Ionov, V.M. Tuchkevich, and I.S. Shlimak, Pis’ma Zh. Eksp. Teor. Fiz. 51, 56 (1990) [JETP Lett. 51, 67 (1990)].

2. O.V. Demicheva, D.N. Rogachev, S.G. Smirnova, E.I. Shklyarova, M.Yu. Yablokov, V.M. Andreev, L.N. Grigorov, Pis’ma Zh. Eksp. Teor. Fiz. 51, 228 (1990) [JETP Lett. 51, 258 (1990)].

3. L.N. Grigorov, O.V. Demicheva, S.G. Smirnova, Sverkhprovodimost’ (KIAE) 4, 399 (1991) [Superconductivity, Phys. Chem. Tech. 4, 345 (1991)].

4. A.V. Krayev, T.V. Dorofeeva, E.I. Shklyarova, L.N. Grigorov, 9th. CIMTEC - World Forum on New Materials, Florence, Italy, 14-19 June 1998; Advances in Science and Engineering Technology, Vol. 23: Science and Engineering of HTC Superconductivity, edited by P. Vincenzini (Faenza Techna., Srl., 1999), pp. 459-466.

5. S.G. Smirnova, O.V. Demicheva, L.N. Grigorov, Pis’ma Zh. Eksp. Teor. Fiz. 48, 212 (1988) [JETP Lett. 48, 231 (1988)].

6. N.S. Enikolopyan, L.N. Grigorov, S.G. Smirnova, Pis’ma Zh. Eksp. Teor. Fiz. 49, 326 (1989) [JETP Lett. 49, 371 (1989)].

7. D.N. Rogachev, L.N. Grigorov, J. Supercond. 13, 947 (2000). The straight dashed lines through the origin shown in Fig. 1 of this paper have smaller slopes than indicated by the labelling for \(\chi\). The values for \(\chi\) given are based on an assumed form of extrapolation of the observed moments to lower fields than those to which they were measured (L.N. Grigorov, personal communication).

8. L.N. Grigorov, D.N. Rogachev, A.V. Kraev, Vysokomol. Soedin. B 35, 1921 (1993) [Polymer Science 35, 1625 (1993)].

9. A.M. Elyashevich, A.A. Kiselev, A.V. Liapzev, G.P. Miroshnichenko, Phys. Lett. A 156, 111 (1991).

10. D.M. Eagles, Physica C 225, 222 (1994); erratum ibid. 280, 335 (1997).

11. D.M. Eagles, J. Supercond. 11, 189 (1998). On p. 192 of this paper, the magnetic moments of two samples inferred from published data were too large by a factor of \(4\pi\), besides having some uncertainty because of lack of precise knowledge by me at that time of the volumes of the samples. This implies that the radii of loops required to fit the moments on the assumption of spontaneous currents close to the critical current can be smaller by a factor of the order of \((1/4\pi)^{1/2}\) than given in the reference. In fact, judging by the magnetisations given in the recent paper for a sample previously reported on in [6], the moments estimated
in [11] for that sample are too large by another factor of two, which appears to have arisen because the low-field susceptibility given in [6] was, I infer from correspondence from Professor Grigorov about reference [7], based partly on an assumed extrapolation of the measured moment curves to lower fields than those for which measurements were made. The smaller moments required from those estimated in [11] give rise to the possibility of alternative explanations in terms of smaller induced currents as discussed in the present paper for the results of [7].

12. D.M. Eagles, Revista Mexicana de Fisica 45, Suplemento 1, 118-121 (1999).

13. L.N. Grigorov, Phil. Mag. B 78, 353 (1998).

14. L.N. Grigorov, 9th. CIMTEC - World Forum on New Materials, Florence, Italy, 14-19 June 1998; Advances in Science and Engineering Technology, Vol. 23: Science and Engineering of HTC Superconductivity, edited by P. Vincennzini (Faenza Techna. Srl., 1999), pp. 675-684.

15. L.N. Grigorov, D.N. Rogachev, Molec. Cryst. Liquid Cryst. 230, 625 (1993).

16. S.G. Smirnova, E.I. Shklyarov, L.N. Grigorov, Vysokomol. Soedin. B 31, 667 (1989).

17. V.M. Arkhangorodskii, E.G. Guk, A.M. El'yashevich, A.N. Ionov, V.M. Tuchkevich, I.S. Shlimak, Dokl. Akad. Nauk. SSSR 309, 603 (1989) [Sov. Phys. Doklady 34, 1016 (1989)].

18. D. Shoenberg, Superconductivity (Cambridge University Press, 1952) Sec. 2.6. Note that in Fig. 12 of this reference, the arbitrary units of magnetic moment used appear to be negative, i.e. opposed to the applied field, as expected. This can be seen from Shoenberg’s equations.

19. W.H. Press, B.P. Flannery, S.A. Teukolsky, W.T. Vetterling, Numerical Recipes (Cambridge University Press, 1986).

20. A.V. Kraev, S.G. Smirnova, L.N. Grigorov, Vysokomol. Soedin. A 35, 1308 (1993). [Polymer Science 35, 1308 (1993)].

21. I.S. Shlimak, L.N. Grigorov, unpublished results, 1996, referred to in [7].

22. S. Senoussi, C. Aguillon, Europhys. Lett. 12, 273 (1990).

23. X.K. Wang, R.P.H. Chang, A. Patachinski, J.B. Ketterson, J. Mater. Res. 9, 1578 (1994).

24. M. Szopper, E. Zipper, Int. J. Mod. Phys. B 9, 161 (1995).

25. I. Shlimak, V. Martchenkov, Solid State Commun. 107, 443 (1998).

26. L.N. Grigorov, T.V. Dorofeeva, A.V. Kraev, D.N. Rogachev, O.V. Demicheva, E.I. Shklyarova, Vysokomol. Soedin A 38, (1996) 2011. [Polymer Science A 38, (1996) 1328].

27. A.N. Ionov, V.A. Zakrevskii, Pis’ma Zh. Tekh. Fiz. 26, No. 20, p. 36 (2000). [Tech. Phys. Lett. 26, 910 (2000)].

28. V.M. Kornilov, A.N. Lachinov, Synth. Met. 53, 71 (1992).

29. V.A. Zakrevskii, A.N. Ionov, A.N. Lachinov, Pis’ma Zh. Tekh. Fiz. 24, No. 13, p. 89 (1998). [Tech. Phys. Lett. 24, 539 (1998)].
30. A.N. Ionov, V.A. Zakrevskii, I.M. Lazebnik, Pis’ma Zh. Tekh. Fiz. 25, No. 17, p. 36 (1999). [Tech. Phys. Lett. 25, 691 (1999)].

31. V.I. Tsebro, O.E. Omel’yanovskii, A.P. Moravskii, Pis’ma Zh. Eksp. Teor. Fiz. 70, 457 (1999). [JETP Lett. 70, 462 (1999)].

32. V.I. Tsebro, O.E. Omel’yanovskii, Phys. Usp. 43, 847 (2001).

33. G.-M. Zhao, Y.S. Wang, cond-mat 011268 (2001); Phil. Mag. B, to be published.

34. D. Djurek, Z. Medunić, A. Tonejc, M. Paljević, Physica C 351, 78 (2001).

Figure Caption

Fig. 1. Comparison of model calculations with diamagnetism associated with closed loops inferred from experiment for applied fields $H_e$ less than the fields at which the metamagnetic transition occurs, i.e. $H_e < 3360$ Oe for sample 1, and $H_e < 1390$ Oe for sample 2. The diamagnetic contribution to the net magnetisation has been inferred from the observed net magnetisation by correction for a probable positive contribution from conducting channels which do not form closed loops (see text).
Theory

Adjusted experimental diamagnetism (see text)