The shape of the resistive transition in superconducting $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_Y$

1990 J. Phys.: Condens. Matter 2 8755

(http://iopscience.iop.org/0953-8984/2/44/004)

J. Phys.: Condens. Matter 2 (1990) 8755–8762. Printed in the UK

The shape of the resistive transition in superconducting $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_Y$

Vladimir V Gridin, Thomas W Krause and W R Datars
Department of Physics, McMaster University, Hamilton, Ontario, Canada L8S 4M1

Received 13 March 1990, in final form 19 June 1990

Abstract. Polycrystalline samples of $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_Y$ with the 108 K superconducting phase show a magnetic field dependent broadening of the resistive transition for temperatures below 118 K. The temperature of the onset of dissipation, $T_d(H)$, decreases as a function of increasing field strength, H. The temperature dependence of dr/dT, where r is the normalized resistance of the samples, indicates the presence of two scattering mechanisms that are responsible for the broadening of the transition when $H \neq 0$. The first mechanism causes a steep increase of dissipation for temperatures that are close to $T_d(0)$. The second one is turned on at $T_d(H)$. We fit the shape of the resistive transition for the temperatures between $T_d(H)$ and 118 K by using the Halperin–Nelson form for the excess of conductivity: $\Delta\sigma \propto \sigma_N \xi_T^2(T)$ and assuming that $\xi_T(T)$ is related to $\xi_E(T)$ and $\xi_I(T)$ via: $\xi_T^{-2}(T) = \xi_E^{-2}(T) + \xi_I^{-2}(T)$, where $\xi_E(T)$ and $\xi_I(T)$ are the correlation lengths attributed to each scattering mechanism.

1. Introduction

The possibility of vortex–antivortex pair dissociation in two-dimensional (2D) superconductors has been proposed by Beasley, Mooij and Orlando (1979) and by Doniach and Huberman (1979) following the theoretical model of 2D phase transitions developed by Kosterlitz and Thouless (1973). A review of recent developments in this field is presented by Minnhagen (1987). The 2D structural transitions are reviewed by Naumovets (1989). Kim *et al* (1989) and Martin *et al* (1989) have discussed the application of the Kosterlitz–Thouless model (1973) to the single crystal data of high-T_C superconducting materials such as TlBaCaCuO and BiSrCaCuO. The latter system has also been studied by Artemenko, Gorlova and Latyshev (1989). Tsuneto (1988) and Ikeda *et al* (1989) have also proposed the Kosterlitz–Thouless 2D model for the explanation of the broadening of the resistive transition.

Another aspect of the reduced dimensionality is the importance of the thermal fluctuations. An excellent review of fluctuation effects in 2D materials has been given by Skocpol and Tinkham (1975) for conventional superconductors. The effect of fluctuations on the conductivity in quasi-2D superconductors has been studied for polycrystalline samples of BiSrCaCuO by Vidal *et al* (1988) and Schnelle *et al* (1989). A study of the fluctuation influenced conductivity in Pb-doped BiSrCaCuO polycrystalline samples has been conducted by Poddar *et al* (1989). Lobb (1987), Kapitulnik *et al* (1988) and many other researchers have considered the importance of fluctuation effects in high-T_C materials.

0953-8984/90/448755 + 08 \$03.50

The formation of a rigid flux lattice is important for the dissipation processes, since a relatively small amount of pinning centers is enough to pin all of the flux lines. Therefore, the flux-lattice melting, which is more important in the 2D systems, could be responsible for the dissipation processes at temperatures well below the critical temperature T_C. The melting of the vortex lattice has been discussed by Nelson (1988) and Brandt (1989). Gammel *et al* (1988), Ota *et al* (1989) and other groups have interpreted their results in terms of the melting of the flux-line lattice.

According to Moore (1989) the melting temperature is reduced as $H^{2/3}$. (See also Markiewicz (1988).) For low and/or intermediate fields (up to 1 T) this has been supported by Rodriguez *et al* (1990) for the BiSrCaCuO single crystals and ceramics.

It is now well established that in the presence of an external magnetic field there is a significant broadening of the resistive transition in BiSrCaCuO. Iye *et al* (1989) point out that the effect is rather intrinsic, since it has been observed in polycrystalline and single-crystal samples. Reports of this behaviour have been presented by Yeshurun and Malozemoff (1988), Palstra *et al* (1988) and other researchers. Tinkham (1988) has used a model of a thermally activated flux-creep to explain this substantial broadening. Iye *et al* (1989) and Fukami *et al* (1989) presented arguments based on their observations which oppose the model of thermally activated flux-creep regime that was used successfully by Anderson (1962) for conventional type-II materials.

In this paper, we show that the broad shape of the resistive transition in the lead-doped BiSrCaCuO polycrystalline samples can be explained and satisfactorily fitted for magnetic fields up to the 1.5 T used in our study. The main suggestion of our empirical analysis is that the resistive transition has contributions from two Kosterlitz–Thouless-type transitions. The first one corresponds to the vortex-antivortex pair dissociation that occurs at a weakly-field-dependent temperature that is close to the zero-field onset of dissipation, $T_d(0)$. The second one occurs at the onset of dissipation, $T_d(H) < T_d(0)$, in an applied magnetic field. The exact nature of this transition, though unknown, is assumed, however, to resemble the dislocation melting of the flux lattice. Fisher (1980) mentions a two step process whereby lattice melting is followed by vortex–antivortex unbinding at T_C. This part is responsible for the remarkable reduction of the temperature of the onset of dissipation when $H \neq 0$. We stress here that in spite of the quite significant agreement between the data and the empirical fitting curves, the physical origin of the second scattering processes might be due to other possible excitations of the vortex system.

2. Experimental results

Details of the sample preparation and the x-ray and DC susceptibility data have been reported by Ummat *et al* (1990). The resistance was measured with a standard four-probe technique. The samples had a rectangular shape with typical dimensions: $L(x) \times L(y) \times L(z) = 0.6 \times 0.2 \times 0.10\ \mathrm{cm}^3$. The external field $\boldsymbol{H}$ was oriented parallel to the smallest sample side, $L(z)$, and the current was set along the $L(x)$ direction. The temperature dependence of the normalized electrical resistance, $r = R(H, T)/R$ is shown in figure 1. The normalization by R enables us to compare samples of different sizes cut from the same material. R is the resistance of our samples at 150 K, with a typical value of 15 mΩ . In figure 2(*a*) we plot the temperature dependence of the derivative $\mathrm{d}r/\mathrm{d}T$. One observes that the position of the maximum is almost field independent for the fields studied. It corresponds to the temperature of the inflection point

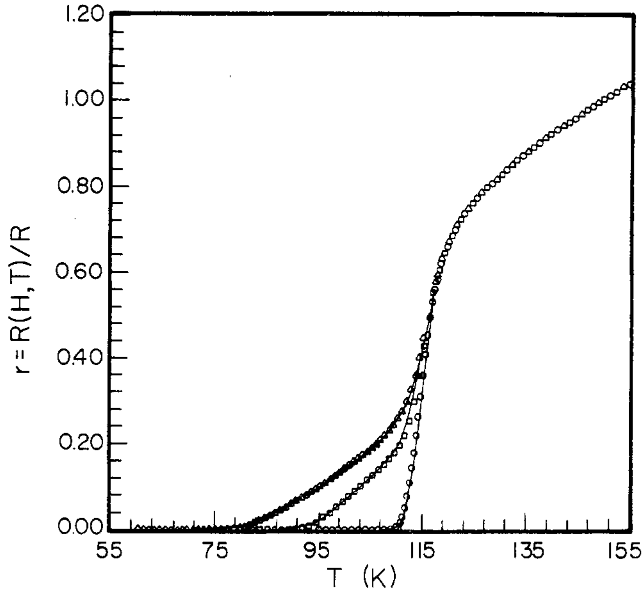

Figure 1. Temperature dependence of the normalized electrical resistance, $r = R(H, T)/R$, of a polycrystalline $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_Y$. For $H = 0$ T, ○; $H = 0.3$ T, □ and $H = 1.1$ T, △. The data are normalized by R at $T = 150$ K with a typical value of 15 mΩ. The solid lines are the best fits through the data in terms of equations (2)–(5) for the temperature range from 118 K to $T_d(H)$, which is defined in figure 2(*a*) as the point of the onset of dissipation.

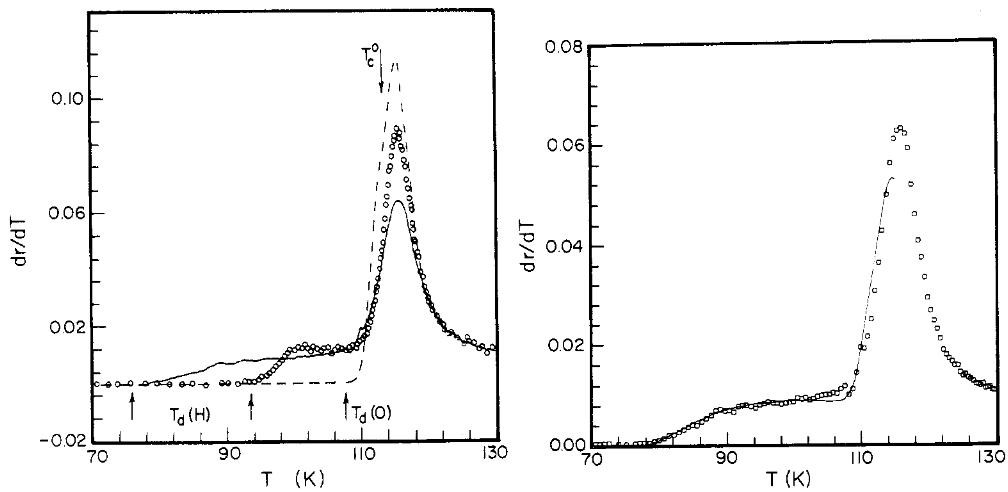

Figure 2. (*a*) Temperature dependence of the derivative dr/dT. $T_d(H)$ and $T_d(0)$ are the temperatures of the departure of dr/dT from its zero level for $H = 0.8$ T, solid line; $H = 0.2$ T, open circles and $H = 0$ T, dashed line. T_c^0 is the fluctuation-corrected BCS critical transiton temperature, that happens to be below the temperature of the inflection point (position of the peak in this figure) for all our samples. (*b*) Temperature dependence of the derivative dr/dT. $H = 0.8$ T, □; the solid line is the derivative dr/dT of the best fit through the data.

of the curves in figure 1. A small, shoulder-like structure below the peak of the zero-field data corresponds to the fluctuation-corrected BCS transition temperature, T_C^0. Gridin *et al* (1990) have analysed the paraconductivity contribution from the superconducting fluctuations in terms of the Aslamazov and Larkin (1968) 2D model and found that the effective thickness of the electronic sheet is 23 Å, i.e. comparable to the separation of the a, b planes. We note that for all our samples $T_C^0 \simeq 113$ K, falls slightly below the position of the inflection point. The temperature of the onset of dissipation, $T_d(H)$, which we define as the point where dr/dT departs from its zero level, shows a remarkable field dependence. The empirical relation between the applied field and $T_d(H)$ is

$$(1 - t_d) = AH^a \tag{1}$$

where $A = 0.28 \pm 0.02$, $a = 0.52 \pm 0.05$ and $t_d = T_d(H)/T_d(0)$, with $T_d(0) = 107.5$ K. This dependence is presented in figure 3, where the straight line is a best power law fit to the data points. The dashed line corresponds to the $H^{2/3}$ behaviour derived by Moore (1989) for the field dependence of the melting temperature of the flux lattice. One observes that the data deviate from the $H^{2/3}$ behaviour for fields $H > 0.5$ T. This agrees with the observation of Rodriguez *et al* (1990). In spite of the deviation from $H^{2/3}$ at higher fields we will assume that the field dependent onset of dissipation is caused, for the fields studied, by the mechanism that resembles the dislocation melting of the 2D flux-lattice crystal. We, now, turn to the more detailed discussion of our results.

3. Discussion

We focus on a general feature, which is the double-step increase in dr/dT in the curves in figure 2(*a*) when $H \neq 0$. The first step occurs near $T_d(H)$ and the second steep increase in dissipation is very close to $T_d(0) = 107.5$ K.

Since the field dependence of $T_d(H)$ presented by equation (1) and figure 3 is reasonably close to the $H^{2/3}$ power law for the temperature dependence of the flux-lattice melting point (at least for $H < 0.5$ T) we suggest that the onset of dissipation at $T_d(H)$ is due to the dislocation melting of the flux lattice. In 2D this process is described by the Kosterlitz–Thouless (1973) structural transition. Nelson (1988) and Markiewicz (1988) have discussed this possibility for high-T_C materials. Brandt (1989) and Moore (1989) have shown that the melting temperature of the flux-line lattice is reduced as a function of magnetic field strength, H. According to Martin *et al* (1989), who used small fields to study the vicinity of the zero-field transition, there is definite evidence of the Kosterlitz–Thouless vortex–antivortex pair-breaking phase transition close to the zero-field onset-of-dissipation point. The second steep increase in our data is attributed to this process.

Let us stress the key points of our analysis:

(i) At $T_d(H)$, we assumed a 'turning on' of a scattering mechanism that resembles in its temperature dependence the dislocation melting of the flux-line lattice which is described by the Kosterlitz–Thouless 2D transition. According to the well known Lindemann's rule this corresponds to a high level of excitations in the vortex system.

(ii) Between $T_d(H)$ and $T_d(0)$ the vortex–antivortex plasma is pictured as a liquid of the vortex–antivortex pairs, with an imbalanced amount of vortices that have their paramagnetic momenta oriented parallel to the direction of the external field. (This point was first discussed by Doniach and Huberman (1979) who took into account the

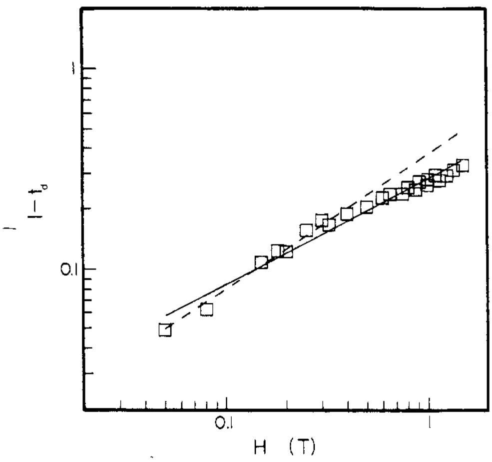

Figure 3. Field dependence of $T_d(H)$, defined in figure 2(a). The straight line is the best linear fit to the empirical observation for this dependence given by equation (1). The dashed line is a $H^{2/3}$ power law, see Moore (1989).

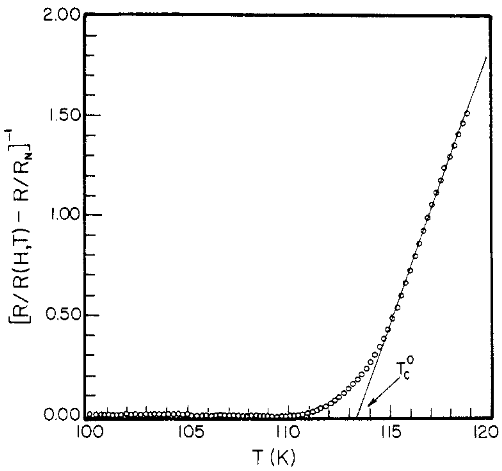

Figure 4. Construction for the evaluation of T_C^0 and the thickness, d, of the quasi-2D superconducting sheet for the zero-field data. See Fiory *et al* (1983) for discussion of the method and Gridin *et al* (1990) for detailed analysis of the data on lead-doped BiSrCaCuO polycrystalline samples, studied here. $T_C^0 = 113.3 \pm 0.2$ K and $d = 23 \pm 2$ Å.

effect of pair breaking by the external field. See also Young (1979), Nelson and Seung (1989) and Marchetti and Nelson (1990) for discussion of the melted phase of the vortex system.) A possible dissipative mechanism in this region is the scattering of vortex–antivortex pairs by unpaired vortices induced by the external field, current, sample imperfections (dislocations, grain boundaries, etc.) and thermal fluctuations. Observe in figure 2(a) that following the initial rise of dr/dT at $T_d(H)$ there is an almost constant rate of the scattering until the temperature approaches the vicinity of $T_d(0)$.

(iii) In the vicinity of $T_d(0)$ there is an additional steep rise in dr/dT that is attributed to the dissociation of the thermally excited plasma of vortex–antivortex pairs. This process is also described by the Kosterlitz–Thouless 2D transition. The temperature interval of this behaviour extends to T_C^0.

(iv) From T_C^0 to 117–118 K, i.e. up to the region of validity of the Aslamazov–Larkin (1968) paraconductivity corrections in our samples, the resistivity is attributed to fluctuation effects towards the superconducting state. In figure 4, we show a typical zero-field construction for finding the thickness of the quasi-2D electronic sheet and the fluctuation corrected BCS critical temperature, T_C^0. (See, e.g. Fiory *et al* (1983) for a discussion of the Aslamazov–Larkin paraconductivity corrections and a description of the construction used in figure 4.) This analysis yields $T_C^0 = 113.3 \pm 0.2$ K and $d = 23 \pm 2$ Å for our samples.

The principal steps of our data analysis are as follows.

(i) We associate a separate correlation length with each of the two Kosterlitz–Thouless processes involved in our model. $\xi_E(H, T)$ corresponds to the separation between dislocation pairs (Halperin and Nelson 1978) in a single sign vortex lattice 'liquid' phase, above $T_d(H)$. $\xi_I(T)$ describes the binding of vortices and antivortices for pair formation. (Subscripts E and I stand for 'extrinsic' and 'intrinsic' correlation, respectively, so that $\xi_E(T)$ corresponds to the 'distance' between centres of mass of dislocation pairs and $\xi_I(T)$ gives the 'size' of a vortex–antivortex pair.)

(ii) To account for the steep rise in the resistivity around 105–108 K we use for $T > 105$–108 K a total correlation length $\xi_T(H, T)$:

$$\xi_T^{-2}(H, T) = \xi_E^{-2}(H, T) + \xi_I^{-2}(T) \tag{2}$$

where $\xi_E(H, T)$ and $\xi_I(T)$ are infinite for $T < T_d(H)$ and $T < T_d(0)$, respectively.

(iii) We use the approximate form suggested by Halperin and Nelson (1979) for the correlation length, $\xi_J(T)$, of the 2D Kosterlitz–Thouless transition:

$$\xi_J(T) \propto B_J \sinh\{b_J \tau_J\} \tag{3}$$

where J = E, I. B_J and b_J are temperature-independent free parameters. τ_J is given by:

$$\tau_E = (T - T_d(H))^{-0.37} \qquad \text{for } H \neq 0 \tag{4a}$$

$$\tau_I = (T - T_d(0))^{-0.5} \qquad \text{for } H = 0. \tag{4b}$$

We use the power law derived by Young (1979) for the temperature dependence of τ_E in the case of the melting of the triangular Abrikosov lattice. The form of equation (3) was chosen, since, according to Halperin and Nelson (1979), its temperature dependence extrapolates well to the limiting behaviours at T_{KT} and above T_C^0. (Here T_{KT} is the temperature of the Kosterlitz–Thouless transition.)

(iv) Using the Halperin–Nelson result for the excess of conductivity, $\Delta\sigma$, in terms of ξ, i.e. that $\Delta\sigma = \sigma - \sigma_N \propto \sigma_N \xi^2$, we write for $r = R(H, T)/R$:

$$r/r_N = 1/(1 + \xi_T^2(T)) \tag{5}$$

where N labels the normal-state transport properties and $\xi_T(T)$ is given by equations (2), (3), (4*a*) and (4*b*). This equation and the sum rule equation (2) follow implicitly from the Halperin and Nelson (1980) form for the coherence length if we consider that ξ_E is also a coherence length between single-sign vortices in the lattice. There are ξ_E^2 phase slip sources per characteristic unit of the vortex lattice. $r = R_N/R = 1.07$ for our samples at T_c^0.

(v) From the best fit of equation (5) to the zero-field data (i.e. when $\xi_T(T) = \xi_I(T)$) we find the values of B_I and b_I. Then, by fitting equation (5) to the field data from $T_d(H)$ to 107.5 K (i.e. up to $T_d(0)$) we obtain the second pair of parameters B_E and b_E, since for this interval according to equation (2) we have $\xi_T(T) = \xi_E(T)$. The final curve is obtained by calculating r/r_N in terms of equation (5) with $\xi_T(T)$ given by the sum rule of equation (2). To account for the slight broadening of the steep rise in the vicinity of $T_d(0)$ we adjusted the values of b_I and τ_I to give a best fit in the whole interval between $T_d(H)$ and 118 K. The corrections never exceeded 1% of the zero-field values for b_I and τ_I. The results of this analysis are shown in figure 1 by the solid lines. We find that the calculated curves agree satisfactorily with the experimental data for the temperature interval ($T_d(H)$, 118 K) for the fields studied. In figure 2(*b*) the more detailed $\mathrm{d}r/\mathrm{d}T$ is compared to the derivative of the best fit for $H = 0.8$ T. The basic structures in the analytical derivative follow the features that are present in the experimental $\mathrm{d}r/\mathrm{d}T$. Since for $T > 117$–118 K the magnetoresistance of our samples is essentially zero we conclude that our qualitative picture accounts well for the total broadening of the resistive transition in an external magnetic field for the fields studied.

Two remarks about the above fitting procedure can be made: first, the parameters B_I and b_I are 0.0085 and 9.56, respectively, for the zero-field data; second, the value of b_E varied between 6 and 10 and are quite close to b_I; however, the parameter B_E was between 0.3 and 0.1 for fields between 0.1 and 1.5 T and was significantly different from the zero-field value of 0.0085. Bearing in mind the qualitative nature of our model and especially the polycrystalline structure of the samples we would not draw any conclusions from the field dependence of B_E.

4. Summary

External magnetic fields result in a remarkable broadening of the resistive transition in polycrystalline samples of $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_Y$. The major increase in resistivity occurs for $T < 118$ K that is slightly above the critical fluctuation corrected BCS temperature, $T_C^0 \simeq 113$ K. The temperature of the onset of dissipation, $T_d(H)$ decreases significantly as a function of the field strength, H and follows the $H^{2/3}$ power law for $H < 0.5$ T. The broadening of the resistive transition with $H \neq 0$ is assumed to be due to the two-step, two-dimensional, Kosterlitz–Thouless phase transition. The first step is due to dislocation melting of the flux-line lattice with the characteristic length scale, $\xi_E(T)$, that describes the correlation between dislocation pairs in the single-sign vortex lattice. The second step is due to the vortex-antivortex pair dissociation with the correlation length, $\xi_I(T)$. Assuming that the total correlation length, $\xi_T(T)$, is related to $\xi_E(T)$ and $\xi_I(T)$ via: $\xi_T^{-2}(T) = \xi_E^{-2}(T) + \xi_I^{-2}(T)$, we fit the shape of the resistive transition for all temperatures between 118 K and $T_d(H)$. The data agree well with the proposed model we feel that the study should be extended to higher fields and carried out on other quasi-2D high-T_C systems (e.g. TlBaCaCuO).

Acknowledgments

We are grateful to Mr T Olech and Mr G Hewitson for their dedicated and highly qualified technical assistance. Thanks are due to Dr P K Ummat for the sample preparation and to Dr C V Stager for helping with the magnetization data of our samples. We acknowledge use of the material preparation facilities of the Institute for Material Research at McMaster University. The research was supported by the Natural Sciences and Engineering Research Council of Canada.

References

Anderson P W 1962 *Phys. Rev. Lett.* **9** 309
Artemenko S M, Gorlova I G and Latyshev Yu I 1989 *Phys. Lett.* **138A** 428
Aslamazov L G and Larkin A I 1968 *Fiz. Tverd. Tela* **10** 1104 (Engl. Transl. 1968 *Sov. Phys.–Solid State* **10** 875)
Beasley M R, Mooij J E and Orlando T P 1979 *Phys. Rev. Lett.* **42** 1165
Brandt E H 1989 *Phys. Rev. Lett.* **63** 1106
Doniach S and Huberman B A 1979 *Phys. Rev. Lett.* **42** 1169
Fiory A T, Hebard A F and Glaberson W I 1983 *Phys. Rev.* B **28** 5075
Fisher D S 1980 *Phys. Rev.* B **22** 1190
Fukami T, Kamura T, Yamamoto T and Mase S 1989 *Physica* C **160** 391

Gammel P L, Schneemeyer L F, Waszczak J V and Bishop D J 1988 *Phys. Rev. Lett.* **61** 1666
Gridin V V, Krause T W and Datars W R 1990 *J. Appl. Phys.* **68** 675
Halperin B I and Nelson D R 1978 *Phys. Rev. Lett.* **41** 121
—— 1979 *J. Low Temp. Phys.* **36** 599
Ikeda R, Ohmi T and Tsuneto T 1989 *J. Phys. Soc. Japan.* **58** 1377
Iye Y, Nakamura S and Tamegai T 1989 *Physica* C **159** 433
Kapitulnik A, Beasley M R, Castallani C and Di Castro C 1988 *Phys. Rev.* B **37** 537
Kim D H, Goldman A M, Kang J H and Kampwirth R T 1989 *Phys. Rev.* B **40** 8834
Kosterlitz J M and Thouless D J 1973 *J. Phys. C: Solid State Phys.* **6** 1181
Lobb C J 1987 *Phys. Rev.* B **36** 3930
Marchetti M C and Nelson D R 1990 *Phys. Rev.* B **41** 1910
Markiewicz R S 1988 *J. Phys. C: Solid State Phys.* **21** L1173
Martin S, Fiory A T, Fleming R M, Espinosa G P and Cooper A S 1989 *Phys. Rev. Lett.* **62** 677
Minnhagen P 1987 *Rev. Mod. Phys.* **59** 1001
Moore M A 1989 *Phys. Rev.* B **39** 136
Naumovets A G 1989 *Contemp. Phys.* **30** 187
Nelson D R 1988 *Phys. Rev. Lett.* **60** 1973
Nelson D R and Seung 1989 *Phys. Rev.* B **39** 9174
Ota S B, Rose R A, Jayaram B, De Groot P A J and Lanchester P C 1989 *Physica* C **157** 520
Palstra T T M, Batlogg B, Schneemeyer L F and Waszczak J V 1988 *Phys. Rev. Lett.* **61** 1662
Poddar A, Mandal P, Das A N, Ghosh B and Choudhury P 1989 *Physica* C **161** 567
Rodriquez E, Duran C, Luzuriaga J, de la Cruz F and Fainstein C 1990 *Physica* C **165** 315
Schnelle W, Braun E, Broicher H, Weiss H, Geus H, Ruppel S, Galffy M, Braunisch W, Waldorf A, Seidler F and Wohlleben D 1989 *Physica* C **161** 123
Skocpol W J and Tinkham M 1975 *Rep. Prog. Phys.* **38** 1049
Stamp P C E, Forro L and Ayache C 1988 *Phys. Rev.* B **38** 2847
Tinkham M 1988 *Phys. Rev. Lett.* **61** 1658
Tsuneto T 1988 *J. Phys. Soc. Japan* **57** 3499
Ummat P K, Datars W R, Gridin V V and Stager C V 1990 *Solid State Commun.* **74** 983
Vidal F, Veira J A, Maza J, Ponte J J, Garcia-Alvarado F, Moran E, Amador J, Cascales C, Castro A, Casais M T and Rasines I 1988 *Physica C* **156** 807
Yeshurun Y and Malozemoff A P 1988 *Phys. Rev. Lett.* **60** 2202