Peak effect in the vortex state of V_3Si: a study of history dependence

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Abstract

We present results of transport properties measurement on a single crystal of V_3Si showing distinct signature of peak-effect in its vortex state. The field variation of the electrical resistance in the flux-line lattice prepared by different experimental path, namely zero field cooling (ZFC) and field cooling (FC), shows a distinct path dependence in the vicinity of the peak-effect regime. In the field cooled state, small cycling of magnetic field modifies the resistance drastically around the peak-effect regime, highlighting the metastable nature of that state in the concerned regime.

I. INTRODUCTION

The A15 superconductor V_3Si has been quite well known over the years both for its interesting normal state [1,2] and superconducting properties [1,3] and the correlation between the two states [3,4]. There is some renewed interest in V_3Si in recent years, first due to the observation of de Haas-van Alphen (dHVA) effect [5,6] , and lately due to the suggestion of the magnetic field induced phase transition in the flux-lattice structure [7]. The observation of dHVA effect in a superconductor is quite puzzling to start with, since the superconducting energy gap is likely to eliminate quantum oscillations. Recent works on V_3Si [5,6,8] and various other superconductors like $NbSe_2$ [9], Nb_3Sn [10], $CeRu_2$ [11], URu_2Si_2 [12] have provided more interesting results, but both the experimental and theoretical situations are yet to be understood completely [8]. In a very recent neutron measurement it has been observed that in certain field direction, the hexagonal flux-line lattice (FLL) of V_3Si distorts with the increase in magnetic field and abruptly becomes of square symmetry [7]. It is suggested that, this transition from the hexagonal to square symmetry may be a first order transition [7]. Phase transition in flux-line lattice (FLL) or vortex state in general, has been a subject of much interest in recent years both from theoretical [13] and experimental [14] points of view. In clean samples of type-II superconductors with weak pinning properties, various topological phase transitions – from a quasi-ordered FLL (or elastic solid or Bragg-glass) to a flux-line liquid, or from a quasi-ordered FLL to a disordered FLL (or plastic solid or vortex-glass) and then to a flux-line liquid– were predicted theoretically (see Ref. 15 and references cited therein), and have subsequently been observed experimentally [16]. It is not clear at this moment whether there is an underlying correlation between the phase transitions associated with the change in the FLL structure (from hexagonal to square symmetry or vice versa) and the field-induced change in topological character (from ordered/quasi-ordered FLL to disordered FLL and/or flux-line liquid) of the FLL. For this purpose it is important to identify various macroscopic as well as microscopic observable associated with the proposed phase transitions in the FLL and study those in details.

Peak-effect (PE) is an important observable for tracking the topological phase transitions (from ordered FLL to disordered FLL) in various high-T_C superconductors (HTSC) [16]. PE is actually a generic term used to describe a peak or local maximum in the field variation of the critical current density (J_C(H)) in various type-II superconductors [17]. In dc magnetization study PE gives rise to a second peak in the field dependence of magnetization [17]. PE and its associated features have been used extensively in recent years to understand the exact nature of FLL phase transitions in various classes of superconductors including both HTSC [16] as well as low T_C [18–21] materials. In a recent theoretical study [22] it is suggested that PE in HTSC materials may be explained by the softening of the FLL due to an underlying structural phase transition from one FLL symmetry to other. This suggestion along with the experimental observation of the structural transition in the FLL of V_3Si (Ref.7) have motivated us to study the superconducting mixed state properties of V_3Si in detail. Although there exist reports of PE in the dc magnetization [23] and transport measurements [24,25] of V_3Si, to our knowledge there exists no suggestion as yet of any topological phase transition (from quasi-ordered elastic FLL to disordered plastic FLL) associated with this PE.

The requirement of a detail study of PE in V_3Si has now become important in the light of various recent developments mentioned above. In this paper we shall present results of our transport properties measurements in a good quality single crystal sample of V_3Si, focussing on PE and various interesting features associated with it. Our results will highlight the field-temperature history dependence of PE and associated metastable behaviour in V_3Si. Based on our present results and other relevant experimental information from the existing literature, we shall also discuss the possibility of a phase transition in the FLL of V_3Si.

II. EXPERIMENTAL

The V_3Si single crystal used in our present study was prepared by Dr. A. Menovski and it is cut from the same mother ingot, part of which was used earlier in de Haas-van Alphen study [6]. While the residual resistivity ratio of the original sample (from which the present sample is cut) was reported to be 47 (Ref.6), our measurements on the present sample yield a residual resistivity ratio of 42. The electrical transport measurements in our present study are performed using standard four probe technique. We have used a superconducting magnet and cryostat system (Oxford Instruments, UK) to obtain the required temperature (T) and field (H) environment. In the configuration of our measurement the current (I_M) is passed along the $< 100 >$ direction of the sample and H is applied perpendicular to I_M. The superconducting transition temperature (T_C) (obtained from our zero field resistance measurement) is 16.5K. We have measured the magnetic field dependence of the resistance R(H) within the following experimental protocols :

1. Cool the sample below T_C to various T of measurement in absence of any applied field H and then increase H isothermally above the upper critical field H_{C2}. This is zero-field cool (ZFC) field-ascending mode.

2. After the above step, decrease H isothermally from above H_{C2}. This is ZFC field-descending mode.

3. Field cool the sample in fixed H from a temperature well above T_C to various temperatures T ($<T_C$) of measurement. This step is repeated for various H at each T. This is field-cool (FC) mode.

III. RESULTS

It is well known that for a sample of type-II superconductor with pinning, the critical current I_C decreases monotonically with the increase in H and goes to zero at the irreversibility field ($H_{irrv} \leq H_{C2}$). This is shown schematically in Fig. 1 (a). However, for superconductors showing PE, I_C(H) shows a peak or local maximum at an intermediate H value before finally going to zero at H_{irrv} (see Fig. 1(a)). The signature of PE will appear in the field dependence of R(H), depending on the magnitude of the measuring current I_M. If $I_M < I_{min}$

(see Fig. 1(a)), R(H) will show zero value up to (depending on the exact value of I_M) almost H_{Irrv} (see Fig. 1(b)). For $H_{irrv} < H < H_{c2}$, R(H) will show flux-flow resistivity leading to the normal state behaviour for $H>H_{C2}$. On the other hand if $I_M > I_{peak}$(H) (see Fig. 1(a)), flux-flow resistivity will start at lower field. In either of these cases, the R(H) will not bear any signature of the PE. The signature of PE will appear in R(H) if $I_{min} < I_M < I_{peak}$ (see Fig. 1(a)). In such a situation a flux-flow resistance is observed with increasing H where $I_M > I_C$(H) but R(H) will fall back to zero in the PE regime where $I_M < I_C$(H) before increasing again at higher field (see Fig. 1(b)). While a direct measurement of the field dependence of I_C would have been very illuminating for the present study of PE in V_3Si, the lack of a suitable current source (with $I_M >$ 100 mA) constrained us to the study of R(H) only. Adjusting the measuring current I_M accordingly, we present in Fig. 2 R vs H plots for V_3Si at various T showing a distinct signature of PE. The (H,T) regime where PE is observed, roughly agrees with that obtained earlier in magnetic measurements [23]. The finer quantitative discrepancy can be attributed to the different residual resistivity ratio of the samples used in the earlier measurement [23] which leads to a small but perceptible change in H_{C2}(T). (It should be noted here that the normal state resistance of the present V_3Si sample above H_{C2}(T) is $\approx$ 40 micro ohm as shown in Figs. 2-5.)

The distinct signature in PE disappears in the H dependence of R(H) for T>15K. The R vs H plots do not show the *reentrant* zero-resistance behaviour for any pre-decided value of I_M between 10mA and 100mA at T=15.5K, although a subtle minimum in R(H) is observed for I_M=20mA (see Fig.3).It should be noted here that the existence of PE in V_3Si was not at all clear in this T regime in the magnetic measurements as well [23].

The PE and the associated features have been very well studied in recent years in the C15-Laves phase superconductor $CeRu_2$ [18–20,26,27]. A very distinct history dependence of PE while cycling H or T was observed in $CeRu_2$ and it was suggested that at the onset of the PE regime, the field cooled (FC) flux-line lattice or the superconducting vortex state of $CeRu_2$ was more disordered than the corresponding ZFC state [26,27]. We shall now investigate the possibility of the same in the present sample of V_3Si. For this, we measure R vs H at various

T following the FC protocol (described above in the experimental section), and the results of such a study are shown in Fig.4. The R(H) measured with the FC protocol is found to be zero even for H-values at which measuring current I_M gave rise to the intermediate H flux-flow regime in the measurements following the ZFC protocol (see Fig.2). This clearly indicates that in the FC mode I_C(H)is greater than I_M in this intermediate H regime, while the opposite is true in the ZFC mode. Thus $I_C(H)$ is higher in the FC mode than in the ZFC mode and this is represented schematically in Fig.1c. To the best of our knowledge this history dependent property of the flux-line lattice of V_3Si has not been reported in the literature so far.

The field cooled FLL at the onset of the PE regime in $CeRu_2$ was reported to be quite metastable in nature [27]. We shall now focus on the FC FLL of V_3Si and check for the metastable behaviour in various H regime. We subject the sample to small field cycling subsequent to the initial FC measurement with an applied H at a particular T. The results of such experiments are shown in Fig.5. We find that within the intermediate H regime, the zero resistance state obtained in the FC mode is destroyed readily on field cycling and the flux-flow resistance corresponding to ZFC state is recovered. This clearly shows the metastability of FC state in the intermediate H regime just below the PE regime. We also note that the minimum value of the cycling field (ΔH) to destroy the metastable FC state, decreases as we move away from the PE regime towards lower field. While we required ΔH=25 mT at H=3.2T to reach the flux-flow resistance of the corresponding ZFC state (see Fig. 5), the recorded value of ΔH at H=2.4T is 5 mT. Below H=1.8T where both ZFC and FC R(H) show zero resistance, the FC state is quite stable and not sensitive to any external field cycling. Inside the PE regime also the field cycling does not have any effect on the FC state. So, it is clear that in the intermediate H regime (where the FC FLL is inferred to be more disordered than the ZFC FLL), the FC state is metastable in nature.

IV. DISCUSSION AND CONCLUSION

The main results of our present study are the following:

1. We see distinct signature of PE in the electrical resistance measurements of V_3Si.

2. There is a clear path dependence in the electrical resistance in the field regime at the onset of PE. This path dependence suggests that the FLL prepared following the FC protocol is relatively more disordered, and can carry more critical current than the FLL prepared in the ZFC protocol.

3. The FC FLL in the intermediate H regime of interest is quite metastable in nature and is sensitive to external fluctuations in the form of field cycling.

A related history dependence of the transport properties in polycrystalline samples of $CeRu_2$, has earlier been reported by Dilley et al [28]. These results of transport properties measurements are correlated to the history effects observed in the PE regime in various magnetic measurements of $CeRu_2$ [20,26,27]. We shall now make a comparative study of the history dependence of PE in V_3Si with the history effects in $CeRu_2$ and $NbSe_2$ where it was argued [18–21,27] that the onset of PE marked a field induced first order transition from a relatively ordered FLL to a disordered FLL. While the origin of this transition as well as the microscopic nature of the high field-high temperature phase remain a matter of debate (see Ref.20), it is generally agreed that on reduction of H and T the system supercools across the first-order transition line [20,21,27,29]. Experimentally observed field-temperature history effects were associated with this supercooling effect (see Ref. 29). This picture of first order transition is further strengthened with the recent theoretical argument (Ref.30) that the range of supercooling while reducing T (i.e. in the FC mode) is more than that obtained through the isothermal variation of H. This is observed experimentally both in $CeRu_2$ (Ref. 27) and $NbSe_2$ (Ref. 21). On comparison, the PE and the associated history dependence in V_3Si turn out to be very similar to $CeRu_2$ and $NbSe_2$. However, it should be noted that the history dependence of the resistance on isothermal reduction of H (from above H_{C2}) is relatively subtle in V_3Si (see inset of Fig.2), and detailed magnetic measurements in the line of those in $CeRu_2$ [18,20,27] are required here. (This will be one of our future projects).

A similar field-temperature history dependence of PE in the transport properties measurements has also been observed in single crystal Nb [31] and thick film samples of Nb_3Ge and Mo_3Si [32]. In these systems the history dependence was associated with the pinning properties of the FLL dislocations [32]. However, while comparing the history effects observed in $CeRu_2$, we argued (Ref. 20 and 27) that the rather fragile nature of the history dependent FLL's cannot be explained easily within such a picture. It would imply that small field excursions anneal out FLL dislocations or any other source of enhanced pinning. And this contradicts the conjecture (Ref. 32) that annealing occurs only when the field is reduced below the peak-effect regime. The fragile nature of FC FLL is clearly shown in our present study on V_3Si. We have also shown that the field cycling ΔH required to destabilize the concerned FC FLL decreases rapidly as one goes away from the PE regime. This is consistent with the theoretical picture that the energy barrier between the higher energy metastable state and the lower energy stable state in the supercooled regime diminishes rapidly on variation of (T,H); supercooling ceases to exist after (T^*, H^*), where barrier height goes to zero and the metastable state is destroyed with infinitesimal fluctuation [30]. We believe that the idea of supercooling associated with a first-order transition probably has an edge over the depinning or annealing of FLL dislocations in explaining the metastable behaviour of FC FLL.

Possibility of some kind of a field induced glass-like transition should also be considered here, especially when it is known that the low diffusivity of a glass can cause metastablities. Such metastabilities, however, are associated with hindered kinetics and not with local minima in free energy. If the metastability arises due to reduced diffusivity, then naive arguments suggest that the metastability will be more persistent when larger motions of particles in configuration space are involved; larger motions are involved when density is varied , rather than when temperature is varied. In the case of FLL a much larger rearrangement of FLL is involved when an (H,T) point is reached by varying H isothermally than when the same (H,T) point is reached by varying T at constant H. Hysteresis would thus be lower in the FC case than in the case of isothermal H variation. This is in contrast of what we have actually observed in the FLL of V_3Si in the vicinity of PE regime and thus negate the possibility of a glass-like transition to be associated with the PE in V_3Si.

We would also like to introduce a third possibility, namely an analogy (if not exact similarity) with the random-field Ising systems (RFIM) where similar field-temperature history effects are well known [34,35]. Most experimental information in RFIM systems has been obtained from studies on various diluted antiferromagnets. In the zero field cooled mode, the diluted antiferromagnet is cooled through the zero-field Neel transition temperature. The resultant antiferromagnetic order thus formed, is preserved when an external magnetic field is subsequently switched on at low temperatures. The long range order, however, gets reduced and ultimately goes to zero on heating the system to the high temperature paramagnetic phase. On cooling back now from the paramagnetic phase in presence of the applied field (i.e. in the field cooled mode), the sample develops a short range ordered domain state [34] in contrast to the long range order ZFC state. The similarity with the FLL state around the PE regime of V_3Si is apparent here, namely the FC FLL is relatively more disordered. Like the FC state of RFIMs, the FC FLL of V_3Si in the vicinity of PE, also becomes unstable on field and temperature cycling [36]; the FC states tend to develop long range order through such cycling process [36]. It is also interesting to note here that the question regarding the underlying phase transition in RFIMs – whether it is a first order phase transition or a continuous second order phase transition–is yet to be settled [37].

We have mentioned in the beginning that a very recent neutron study has shown the existence of a field induced structural transition from hexagonal to square symmetry in the FLL of V_3Si (Ref.7). Such a structural transition is capable of softening the FLL and can give rise to a PE [22]. Moreover, if the structural transition in the FLL of V_3Si is indeed a first order transition as was speculated in the aforementioned neutron study [7], then all the experimentally observed history dependence of PE in V_3Si may find a natural explanation in terms of this first order phase transition. However, we must note that the reported structural transition in FLL takes place at a rather low field value of about 1.3T at 1.8K. Unless there is a strong nonmonotonic temperature dependence of the onset field of PE in magnetic and transport measurements as is observed in the case of untwinned single crystals of YBCO (Ref.38), any simple correlation between PE and structural transition will not be valid. Future measurements of magnetic and transport properties down to 1.8K and/or neutrom measurements in the temperature regime 12K and above will settle this question.

Softening of the FLL in a type-II superconductor may also arise due to a change in the character of the underlying superconducting order parameter. It was argued by Fulde and Ferrel [39], and independently by Larkin and Ovchinnikov [40] that in a superconductor with substantial normal state paramagnetism, a partially depaired superconducting state was energetically more favorable than the isotropic BCS state. The superconducting order parameter in this high field state (which is often termed as Fulde-Ferrel-Larkin-Ovchinnikov (FFLO) state) vanishes periodically (with a period of 10-40 times of the coherence length ξ_C) along the direction of the applied field H [41]. These nodes in the order parameter can transform the three dimensional rigid flux-lines at lower H into a quasi-two dimensional structure at the onset of the FFLO state [41] at higher fields. A FLL with such a quasi-two dimensional structure is relatively more soft and can give rise to a PE. Moreover, since the transition to the FFLO state is a first order transition, any system undergoing a FFLO transition should show along with the PE, the history effects associated with supercooling. Although in mid nineties $CeRu_2$ and the heavy fermion superconductor UPd_2Al_3 were thought to be prime candidates for the FFLO state [42,43], there remain several arguments against the existence of such a state in those systems (see Ref. 19 and 44). It should be quite instructive now to check whether V_3Si meets the following necessary conditions for the existence of the FFLO state :

1. The first condition that such a system should be in the clean limit is easily met for the present single crystal sample of V_3Si (Ref.6) as well as in the other samples of V_3Si where PE was observed earlier [23].

2. The second question, whether the upper critical field H_{C2} of V_3Si is clearly Pauli limited or not, is difficult to answer. The $H_{C2}(0) \approx 18.5$ T [6,23] is lower than the Pauli limiting field H_P=1.84 × T_C Tesla/K ≈30T. However, the effect of Pauli paramagnetic limiting process is thought to be quite important for the superconducting properties of V_3Si [45]. It should be noted here the expression for H_P was derived for a system with spherical Fermi surface and its application to a system with apparently complicated Fermi surface should be made with some caution. It is now known that the nesting properties of the Fermi surface actually helps to stabilize the FFLO state in a system [46]. Also electron correlation effect is known to influence the value of H_P in V_3Si [47].

3. While in earlier theoretical works [48] the FFLO state ceased to exist for $T \geq 0.57 T_C$, the extent of FFLO state in various systems is found to be up to $\approx 0.9 T_C$ (Ref. 41). While PE was not observed in V_3Si for T>15K in magnetic measurements [23], in our present transport study the field induced zero resistance state associated with the PE is observed up to 15K only. However, we have observed a local minimum (but not the re-entrant zero resistance state) in the R vs H plot for T>15K . This resistance minimum, unlike the re-entrant zero resistance in the regime T≤15K, is path independent.

The above discussion should by no means be taken as a support for the existence of the FFLO state in V_3Si, but emphasizes that more studies, especially measurements probing the microscopic properties of the superconducting states, are required to reach a definite conclusion.

We must mention that a relatively simpler argument for PE is also possible in V_3Si in terms of minute microscopic inhomogeneity present even in the single crystals of V_3Si [49]. Regions with slightly different superconducting properties can act as additional pinning centers at high fields, in a similar manner as the oxygen deficient centers in the HTSC material YBCO [50], and give rise to PE. However, the magnetic history dependence of PE cannot have any simple explanation within such a picture.

In conclusion, our study of the peak effect in V_3Si has revealed interesting history effects and metastable features associated with it. These results can be explained in terms of a first order phase transition in the flux-line lattice of V_3Si. It is interesting to note here that very recently history effects and associated metastable features have been observed in the crossover regime from Bragg-glass to vortex-glass in single crystal samples of YBCO [51]. Very recent magneto-optic studies in single crystal samples of BSCCO claim the presence of phase co-existance [52] and supercooling across the Bragg-glass to vortex-glass phase transition [53]. These, in turn, suggest the possibility of a first order transition. Josephson plasma resonance study in single crystal samples of BSCCO also support this picture [54]. In this context, our present results on the well known A15 superconductor V_3Si are likely to provide useful information on the universality of the problem.

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FIGURES

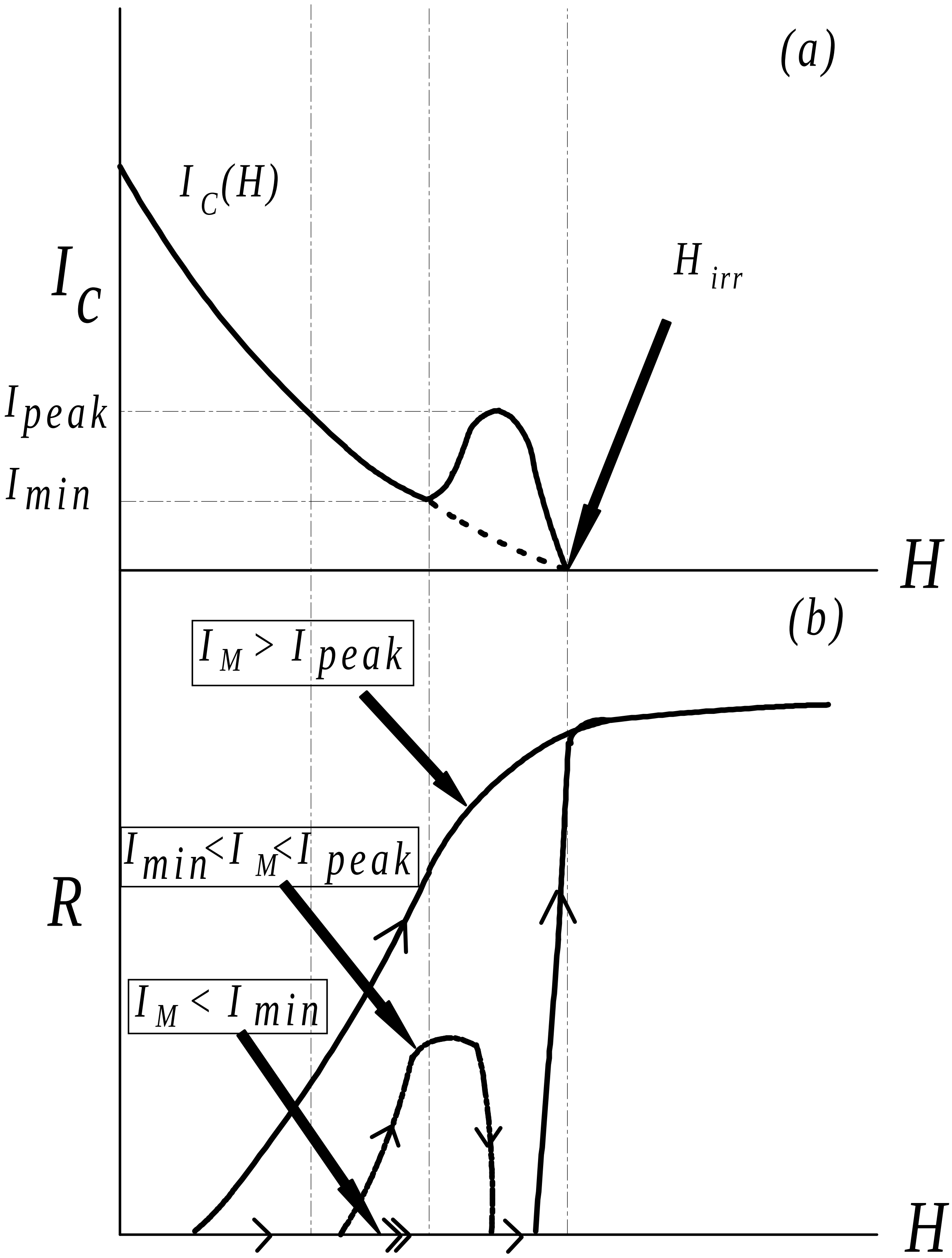
FIG. 1. (a)Schematic representation of field (H) dependence of critical current (I_C), highlighting the peak-effect near H_{C2}. In the absence of peak-effect, I_C would have gone to zero monotonically (at H_{irrv}) as shown by the dashed line. (b) Schematic representation of field (H) dependence of electrical resistance for various values of the measuring current (I_M) – $I_M < I_{min}$, $I_{min} < I_M < I_{peak}$ and $I_M > I_{peak}$. (c)Schematic representation of the field dependence of I_C(H) obtained in the ZFC field-ascending mode. A history dependence of I_C(H) has actually been observed experimentally in various other type-II superconductors. For an early detailed study on a strained single crystal of Nb see M. Steingart, A. G. Putz and E. Kramer, J. Appl. Phys. **44**, 5580 (1973).

FIG. 2. Resistance (R) vs field (H) plot for V_3Si obtained in the ZFC-field ascending mode at 13.5K (with I_M = 100 mA), 14.5K (with I_M=85 mA) and 15 K (with I_M=40 mA). Inset shows the R vs H plot for V_3Si obtained in the ZFC-field ascending (filled square) and ZFC-field decscending (open square) mode at 13.5K with I_M = 100 mA.

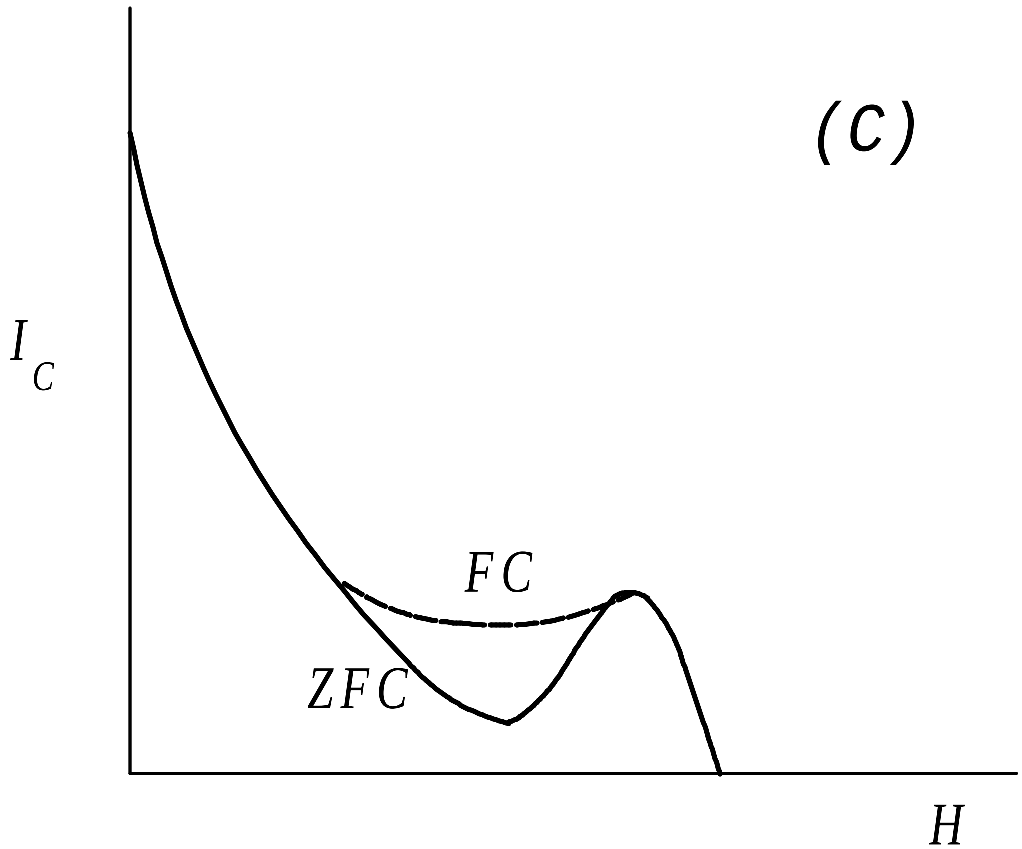
FIG. 3. Resistance (R) vs field (H) plot for V_3Si obtained in the ZFC mode at 15.5K with I_M=10, 20 and 40 mA.

FIG. 4. Resistance (R) vs field (H) plot for V_3Si obtained in the FC mode at 13.5K (with I_M = 100 mA), 14.5 K (with I_M=85 mA) and 15 K (with I_M=40 mA).

FIG. 5. Metastable behaviour of R(H) of V_3Si obtained in the FC mode at 14.5K with I_M =85 mA. Filled square denote R(H) values obtained after field cooling in various H values. Filled triangles denote R(H) values obtained after a field cycling of maximum ΔH subsequent to the first FC measurement at the corresponding H. The magnitude of ΔH depends on H (see text for details). Open square denotes data obtained in the ZFC mode at 14.5K (as in the case of Fig.2).



(a)
$I_C(H)$
I_C
H_{irr}
I_{peak}
I_{min}
H
(b)
$I_M > I_{peak}$
$I_{min}<I_M<I_{peak}$
R
$I_M < I_{min}$
H


(c)
I_C
FC
ZFC
H

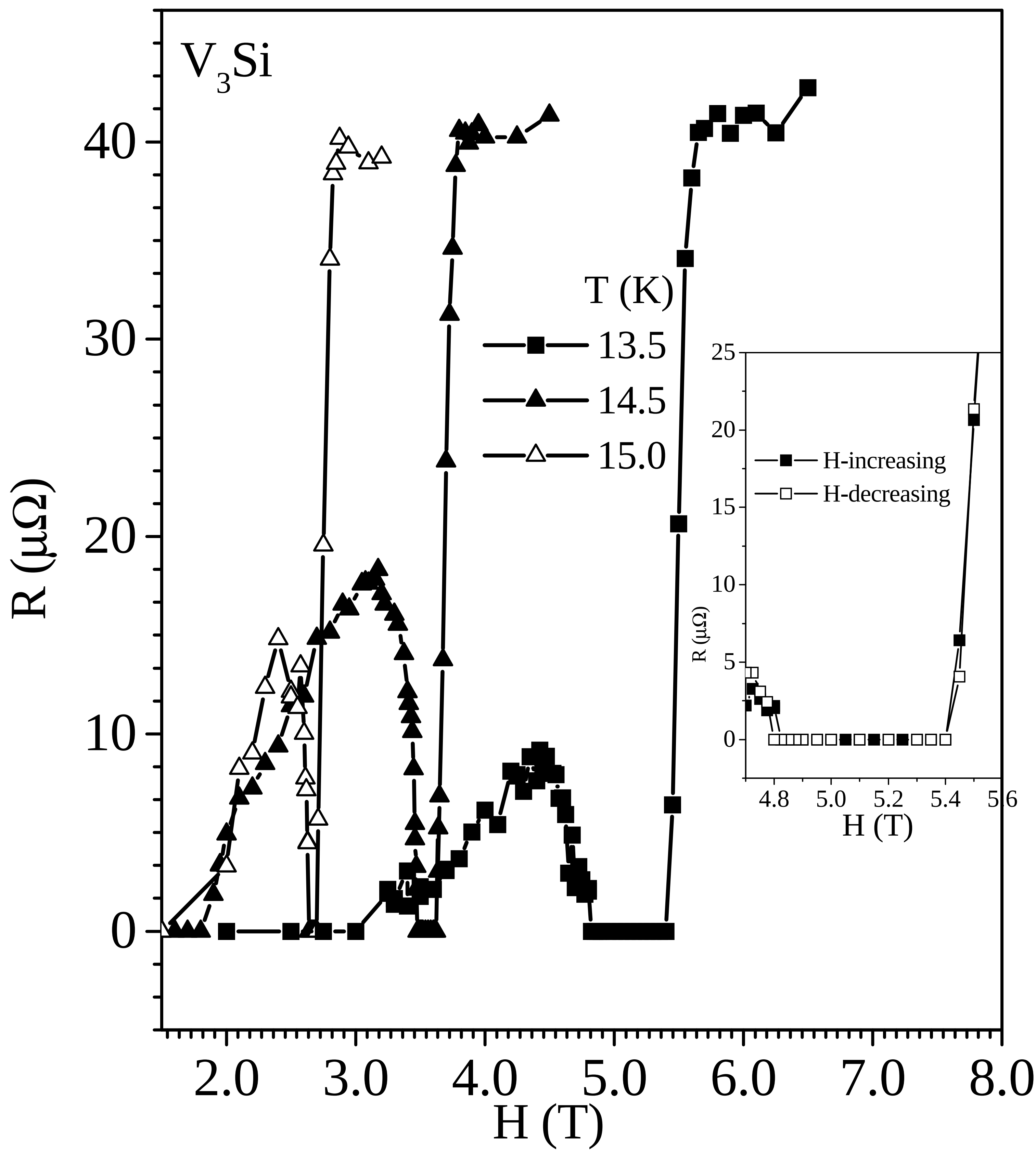
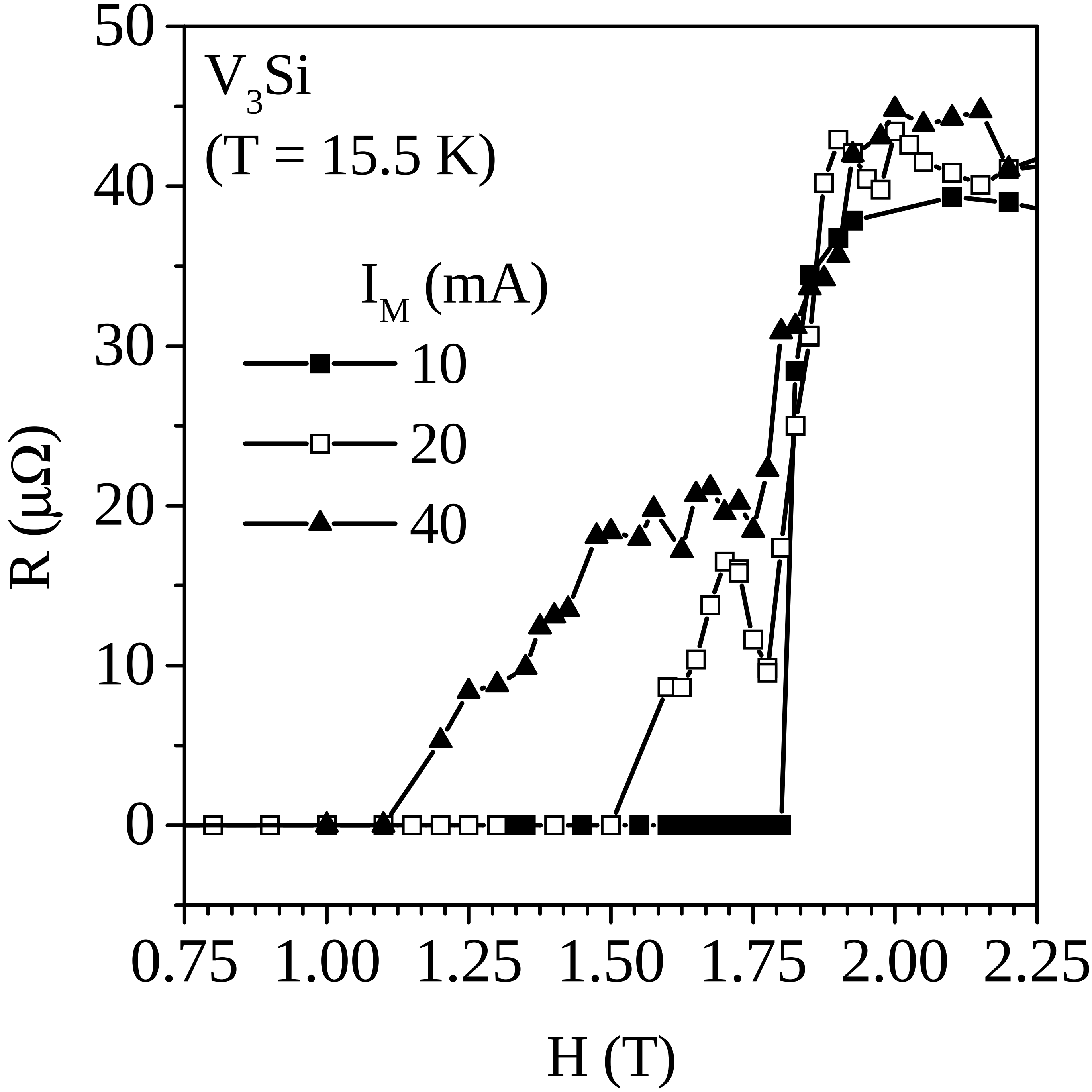

V3Si
T (K)
13.5
14.5
15.0
R (μΩ)
H (T)
H-increasing
H-decreasing
40
30
20
10
0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
25
15
5
4.8
5.2
5.4
5.6

Fig. 2 of 5



V3Si
(T = 15.5 K)
IM (mA)
10
20
40
R (μΩ)
H (T)
50
40
30
20
10
0
0.75
1.00
1.25
1.50
1.75
2.00
2.25

Fig. 3 of 5

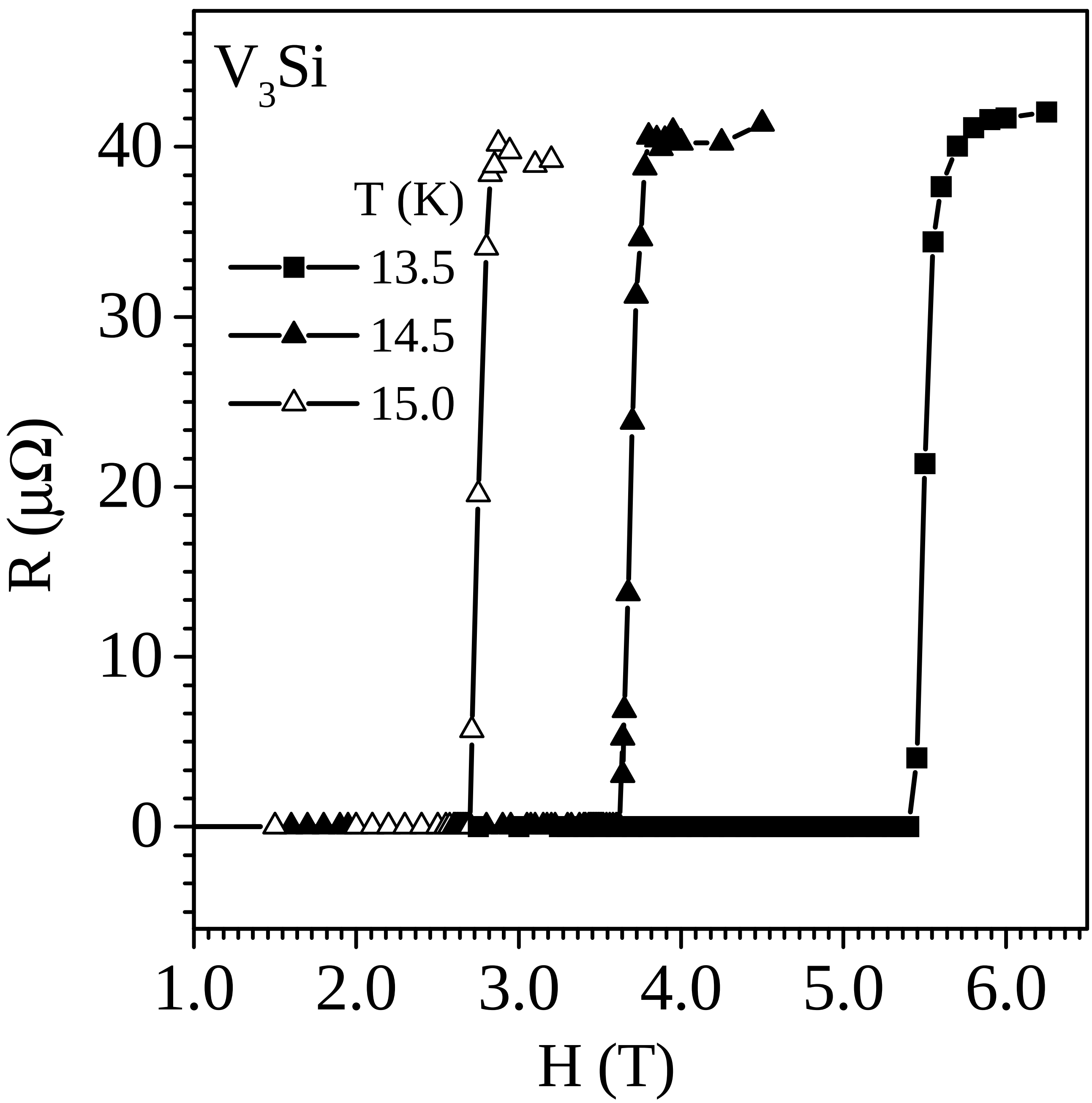


Fig. 4 of 5

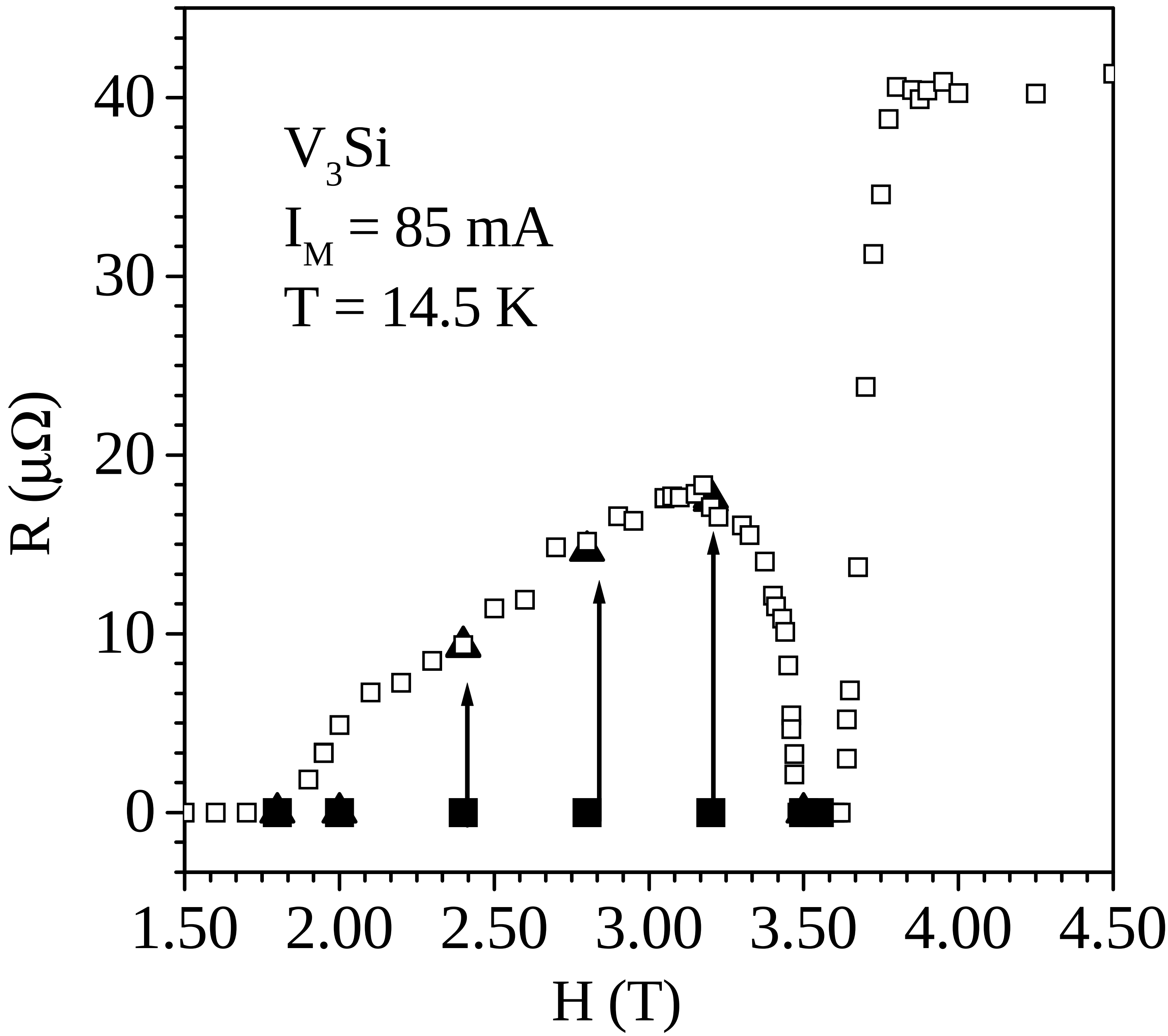

V3Si
IM = 85 mA
T = 14.5 K
R (μΩ)
H (T)
0
10
20
30
40
1.50
2.00
2.50
3.00
3.50
4.00
4.50

Fig. 5 of 5