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Local Magnetometry of Superconducting Mo_8Ga_{41} and Mo_7VGa_{41}: Vortex Pinning Study

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Endohedral gallide cluster superconductor Mo_8Ga_{41} indicated some unusual superconducting properties that deviated from BCS theory. This was ascribed to possible multi-gap superconductivity. Moreover, these properties seem to vanish after the substitution of vanadium atom for molybdenum. Here, we present a local magnetization study of both compounds, Mo_8Ga_{41} and Mo_7VGa_{41}. An array of miniature Hall probes was used to study magnetic profile which reflects vortex distribution inside the sample. The vortex pinning observed in both materials is strong. Calculated critical current density values suggest, that vortex pinning in Mo_8Ga_{41} manifests itself to a greater extent than in Mo_7VGa_{41}.

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1. Introduction

Recent thermodynamic studies of Mo_8Ga_{41} superconductor have revealed some nontrivial features [1]. It was suggested that it might be due to two-gap superconductivity in the compound [2]. Moreover, this two-gap behavior seemed to vanish upon vanadium substitution [2]. The authors studied the samples using muon spin rotation/relaxation (μSR) technique. From measured σ_{sc}, i.e., the superconducting contribution to the muon spin relaxation rate, they calculated upper critical magnetic field $\mu_0 H_{c2}$ and magnetic penetration depth λ using a model proposed by Brandt [3]. In case of Mo_7VGa_{41}, they found a good agreement between the value of $\mu_0 H_{c2}$ resulting from the model, and the value observed in the thermodynamic measurements, while in Mo_8Ga_{41} the model value was significantly reduced. This indicates two or more distinct length scales in the superconducting state in the latter case. However, recent follow-up study [4] clearly excluded two gap superconductivity in this compound. Precise thermodynamic and spectroscopic measurements revealed multi-phase character of the Mo_8Ga_{41} sample, and the only one intrinsic superconducting energy gap was stated [4]. As mentioned before, two-gap superconductivity in Mo_8Ga_{41} [2] was originally proposed based on discrepancies between thermodynamic data and results from σ_{sc} model. The validity of the model is, according to Brandt [3], limited to a case of the ideal periodic flux-line lattice formation, i.e., superconductor without vortex pinning. The aim of this study is to determine, whether the vortex pinning in the sample is really absent. We addressed this aim using Hall-probe magnetometry, which can detect presence of the vortex pinning, and also determine its strength.

2. Experimental details

Both samples Mo_8Ga_{41} and Mo_7VGa_{41} were synthesized using the flux growth method described in detail in [1]. For the crystal characterization see [4]. Both samples were of sub-millimeter dimensions. A vortex pinning study has been performed using an array of miniature Hall probes. Such Hall probe array was based on semiconductor heterostructures GaAs/AlGaAs with two-dimensional electron gas in the active layer, and was designed and manufactured at the Institute of Electrical Engineering SAS in Bratislava [5]. In total, eight probes with the size of 10×10 μm^2 are arranged in line with the 25 μm pitch of their centers. The sample was placed on top of the array, mounted in ^{3}He refrigerator, and installed in 8 T superconducting horizontal magnet. Probes with the sample on the top were oriented perpendicular to the applied magnetic field. In order to eliminate the magnetic field trapped in the samples, they were cooled in zero magnetic field before each measurement. Probes were serially powered by a constant current. Voltage measured across the probes was proportional to the local magnetic induction of the sample. During the measurement, applied magnetic field

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was increased gradually, and the voltage of the probes was recorded. In the ideal case when a superconducting sample is in the Meissner state, probes covered by the sample will be shielded, and the voltage measured across them will not change. However, due to the non-zero distance between probes and the sample, all data showed actually a small initial linear increase of the Hall voltage, which was removed prior to data treatment. Due to the shape of the sample, the surrounding magnetic field is deformed, effectively stronger around the sample edges. When this effective field reaches the value of lower critical magnetic field H_{c1} everywhere around the sample, then the first vortex penetrates inside, while applied magnetic field reads the value H_p, called penetration field. The relation between H_{c1} and H_p is given by the sample's geometry [6]. By further increasing the applied field, the Hall voltage will increase significantly as a result of a growing number of vortices passing through the sample. When entering the sample, the vortex tendency is to move to the sample center due to the repulsive interaction with the superconducting current flowing beneath the surface of the superconductor. If there is no vortex pinning in the sample, the spatially extended Meissner current results in effective trapping of vortices in the center of the sample because of geometrical barriers [7]. In this case Hall probes underneath the sample center will respond with a higher voltage than those near the edges. It will result in the dome-shaped magnetic profile for increasing magnetic field — a characteristic sign for the absence of vortex pinning [7]. On the other hand, if there is a strong vortex pinning in the sample, pinning centers will prevent the movement of the vortices, so they will accumulate near the edges of the sample. As opposed to the previous case, probes closer to the edges will respond with higher Hall voltage, thus the magnetic profile will be V-shaped, according to Bean model [8]. When the applied field increases, the vortices will be progressively pushed towards the center of the sample.

3. Results and discussion

By a parallel recording of the Hall voltage of all probes across the sample with gradually increasing magnetic field, we were able to construct magnetic profiles for Mo_8Ga_{41} (Fig. 1a) and for Mo_7VGa_{41} (Fig. 1c). Both Mo_8Ga_{41} and Mo_7VGa_{41} samples were wider than the total Hall probe array length, thus it was necessary to measure profiles by parts, by shifting of the sample on the probe array. In result, profiles were constructed from two overlapping positions. Individual curves in Fig. 1 represent magnetic profiles of the sample in a certain magnetic field (distinguished by different colors). The horizontal axis of each graph is normalized to half of the width of the sample $w/2$. It represents the relative distance from the center of the sample. Auxiliary vertical dashed lines delimit the width of the sample. Points lying between those lines depict magnetic induction B_z across the whole sample at different magnetic

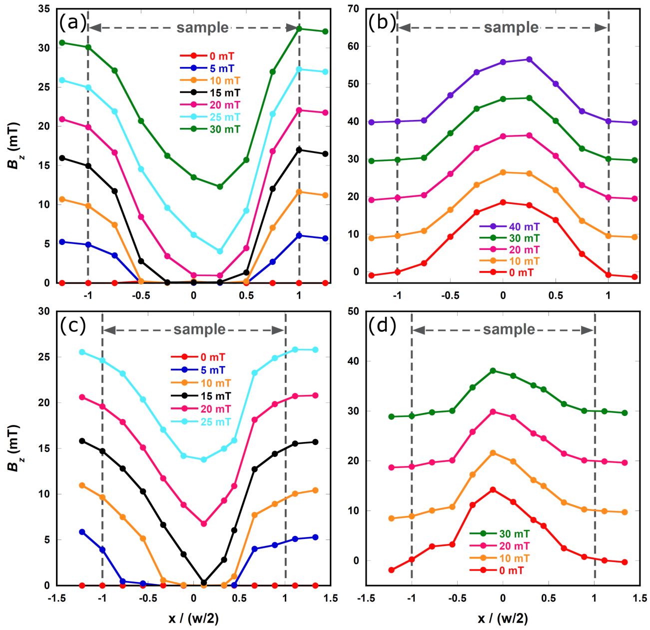

Fig. 1. Magnetic profiles of the samples measured at 2 K: (a) Mo_8Ga_{41} for increasing field, and (b) for decreasing field, (c) Mo_7VGa_{41} for increasing field, and (d) for decreasing field. The horizontal axis represents the relative distance $x/(w/2)$ from the center of the sample, w is the width of the sample. Vertical dashed lines correspond to the position of the sample edges. Points depict magnetic induction B_z of the sample at different applied magnetic fields (different colors). Lines that connect the points are guide to the eyes.

fields. Points lying outside this area represent measured magnetic induction around the sample. As mentioned before, the shape of the magnetic profile when increasing applied magnetic field is very important to identify whether the vortex pinning occurs in the sample. Indeed, both profiles (Fig. 1a and Fig. 1c) are V-shaped, which only means that vortex pinning is strong in both cases.

Magnetic profiles of Mo_8Ga_{41} and Mo_7VGa_{41} in decreasing magnetic field, are displayed in Fig. 1b and Fig. 1d, respectively. In this scenario, vortices stay pinned and gradually with decreasing field leave the sample through its edges. When applied field drops to zero, some vortices still persist pinned, and so magnetic induction B_z of the sample is not equal to zero. Its value acquires maximum value B_r in the center of the sample, while decreases towards the sample edge. The pinning strength can be expressed by the critical current density J_c, given by formula $J_c = 2B_r/w$, where w is the sample width. Thus, the gradient of the magnetic induction inside the sample mirrors the pinning strength. For Mo_8Ga_{41} sample ($w = 180$ μm) we have $J_c = 16\,348$ A/cm^2, and for Mo_7VGa_{41} sample ($w = 240$ μm) we obtain $J_c = 9\,450$ A/cm^2. Calculated values of critical current density J_c differ and suggest that vortex pinning is stronger in Mo_8Ga_{41}. For comparison, P. Neha et al. [9] reported $J_c \sim 3 \times 10^5$ A/cm^2, which is even one order of magnitude higher value, although observed at the same temperature $T = 2$ K. Strong pinning in both samples casts doubts on suitability of the model used in μSR study. It remains an open question why the results of the μSR were so different for Mo_8Ga_{41} and Mo_7VGa_{41} assuming that both samples are single-gap superconductors with strong pinning. One possible explanation is that the multi-phase character of the sample is more pronounced in Mo_8Ga_{41}. This difference will be subject of future studies.

4. Conclusions

A vortex pinning study was carried out by local magnetometry on two related gallide compounds Mo_8Ga_{41} and Mo_7VGa_{41}. Magnetic profiles of both samples were constructed for gradually increasing and decreasing applied magnetic field. V-shape magnetic profiles observed in both materials revealed the presence of strong vortex pinning. Calculated values of critical current density J_c for Mo_8Ga_{41} and Mo_7VGa_{41} suggest that vortex pinning is stronger in Mo_8Ga_{41}. These findings cast doubts on suitability of the model used in previous studies.

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