# Electrical transport, magnetic, and structural properties of the vortex lattice in superconducting $V_3Si$

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**Abstract**

Electrical, magnetic, and structural properties of the vortex lattice (VL) in single crystal $V_3Si$ were studied by transport, bulk magnetometry and small-angle neutron scattering. Studies focused on the 'peak effect' in critical current density just below the upper critical field of this weak-pinning system. The overall picture is a slightly disordered VL easily re-ordered by transport-current 'shaking' and ultimately softening at the peak effect.

*Key words:* vortex lattice; metastability; peak effect; transport; SANS; flux pinning; $V_3Si$

The well-known 'peak effect' in critical current density $J_c$ has attracted renewed attention after it was found to exist in both high-temperature- and conventional superconductors. Although this was traditionally explained in terms of competition between the elasticity of the vortex lattice (VL) and the pinning energies, with the softening of the lattice close to the superconducting transition giving way to disorder and more effective pinning [1,2], recent studies [3] have called this picture into question. The traditional picture is found to be most applicable to the investigation regime and results of this study.

A complication in studying the peak effect in anisotropic and/or high-temperature superconductors is the influence of thermal fluctuations. In this study, thermal activation is strongly suppressed by the use of clean, high-$\kappa$ ($\kappa = 25$), weakly pinned single-crystal samples of the 'conventional' A15 (cubic symmetry) superconductor $V_3Si$. The samples were cut from the same cylindrical crystal used in Ref. [4], with an estimated mean free path $l = 320$ Å$\gg \xi_o = 38$ Å, a critical temperature $T_c$ of 16.3 K, and extrapolated $H_{c2}(0)$ of about 22 T. The Ginzburg number, which quantifies the significance of thermal effects, is estimated to be about $10^{-7}$, which would *a priori* eliminate any measurable possibility of a melting transition separate from the superconducting transition [5].

In this study we combine data from small-angle neutron scattering (SANS), magnetization measurements, and transport measurement, all on samples from the same crystal ingot. All measurements were done with the field applied parallel to the crystallographic $\langle 110 \rangle$ direction. The neutron scattering was conducted on a cylindrical section using horizontal-field geometry at various constant fields as a function of temperature and thermal history. Magnetization was measured on a disk section using a SQUID Magnetometer, with the field along the central axis and as a function of applied magnetic field and temperature. A 1 mm square rod sample was used for transport current-voltage ($V(I)$) measurements using a standard, low-resistance, 4-contact strip configuration, with the field perpendicular to the length of the rod. The applied current for each data point consists of one alternating cycle consisting of two 30 ms square pulses separated by a 2 s null signal; the null pause between consecutive data points is approximately 3 s. Voltage is measured during a smaller interval within each current pulse.

The intensity of a first-order Bragg diffraction spot from SANS was found [6] to decrease monotonically

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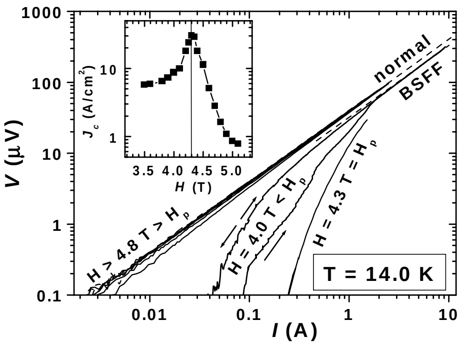


Fig. 1. Transport $V(I)$ curves at some fields about $H_{\rm p}$ for $T$ = 14.0 K. Inset: corresponding $J_{\rm c}$ $(H)$ peak. (See text.)

with increasing temperature, vanishing to background values only at the temperature $T_{\rm p}$ corresponding to the peak effect for this field, suggesting well-defined VL structure without melting. In conjunction with this is an azimuthal and radial broadening of the Bragg spot towards $T_{\rm p}$. These are consistent with the highly ordered, so-called Bragg glass, with steady encroachment of disorder as pinning eventually overwhelms the elasticity of the VL and vortices accommodate themselves to pinning sites. However, long-range order exists all the way up to $T_{\rm p}$, well above the magnetically determined irreversibility temperature (see below), with no evidence of polycrystalline structure. In addition, at each temperature the intensity was slightly higher and the breadth narrower when field-warming from 2 K, compared to field-cooling from above $T_{\rm c}$, indicating 'healing' of metastabilities at low temnperatures.

Magnetization was observed [6] to be nearly reversible over a wide range of fields, starting at a field $H_{\rm irr}$ and extending well toward $H_{\rm c2}(T)$, below which an irreversibility loop occurs, marking the peak effect in $J_{\rm c}$. The weakness of this effect confirms the weak pinning in this very clean system and the absence of thermal activation. The same kind of subtlety was also seen in the temperature domain. The near-reversibility of the magnetization between $H_{\rm irr}$ and the peak-effect field $H_{\rm p}$ translates to a voltage scale that yields a small but measurable $J_{\rm c}$ using transport current. At fields below $H_{\rm irr}$, pinning increases as VL elasticity declines at more dilute vortex densities while pinning forces increase.

Transport $V(I)$ measurements were taken over a wide range of temperatures and fields in the vicinity of the peak effect $H_{\rm p}(T_{\rm p})$. Typically, logarithmic plots of $V(I)$ were found to rise rapidly with current and saturate to slope = 1 at high current levels, again implying the absence of melting. This is shown in Fig. 1, where temperature was held constant and $V(I)$ is shown for a few fields about and including $H_{\rm p}$. The inset shows the corresponding peak effect in $J_{\rm c}$. For $H < H_{\rm p}$, consistent with previous studies of $NbSe_2$ [7], the virgin VL was found to be metastable, as manifested by an irreversible, higher-$I_{\rm c}$ $V(I)$ curve. From this state, we have found [6] that a reversible, lower-$I_{\rm c}$, and temporally stable $V(I)$ could be reproducibly obtained by the 'shaking' action of the pulsed current at high enough levels, thus suggesting a coexistence of ordered and disordered phases in the virgin VL. Stable $V(I)$ curves for $H < H_{\rm p}$ were found to be ohmic over a wide range of $J > J_{\rm c}$, and a simple calculation confirms that the resistivity corresponding to this linear portion is well below the expected normal-state level; instead it coincides with the level expected for ordered, Bardeen-Stephen flux flow (BSFF). For $H > H_{\rm p}$, $V(I)$ at high currents approaches the level expected for normal-state resistivity. At $H = H_{\rm p}$, the $V(I)$ curve was found to remain below either level, indicative of the maximal pinning.

The resulting magnetic phase diagram [6] confirms consistency between transport data and magnetization data. The overall picture is that of a virgin VL with significant long-range order coexisting with slight imperfections which are easily erased by current-driven agitation, as facilitated by strong, elastic interaction among the vortices. As the peak effect is approached, competing order and disorder (pinning) culminate in a crossover between pinning energy and elastic energy. Therefore the well-known picture of VL softening [1,2] is sufficiently applicable, at least for these fields and temperatures, which are much higher than in similar studies on other conventional superconductors [7,8].

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