First- and Second-Order Superconducting Phase Transitions of Tin Whiskers in a Magnetic Field

D. S. McLachlan

Solid State Physics Research Unit, Department of Physics, University of the Witwatersrand, Johannesburg, South Africa

(Received August 9, 1971)

Using a sensitive inductance technique, first- and second-order phase transitions in tin (type I) whiskers have been observed in both parallel and perpendicular magnetic fields. For $T$ much less than $T_c$ the samples exhibit considerable superheating and supercooling from which values of the Ginzburg-Landau parameter $\kappa$ are calculated. However, these values are not as low as those obtained for single spheres (diameters 10-30 $\mu$), probably due to mean free path and size effects. Close to the transition temperature it is observed that the hysteresis vanishes indicating the onset of a second-order phase transition. Good qualitative agreement between these results and theoretical predictions based on the Ginzburg-Landau theory are obtained. Size effects on the ratio $H_{c3}/H_{c2} = H_{sc}/H_{c2}$ are clearly illustrated.

1. INTRODUCTION

Tin whiskers are known to have irregular cross sections$^{1,2}$ with dimensions of the order of 1 $\mu$, and can be strained elastically up to 2%, presumably due to the absence or pinning of defects such as dislocations.

A study of the superconducting phase transitions of these whiskers was undertaken for the following reasons. (i) Their small cross section makes it possible to study the onset of the second-order phase transition in a magnetic field, which occurs when the temperature-dependent penetration depth $\lambda(t)$ ($t = T/T_c$) becomes of the order of the “radius” of the whisker.$^3$ (ii) Well below $T_c$, where $\lambda(t)$ is small compared to the cross section of the whisker and the transition is a first-order one, the probable absence of bulk defects, which can act as nucleation sites, could lead to the observation of considerably more superheating and supercooling (lower $\kappa$ values) than has previously been observed.$^4$ Reference 4 contains an up-to-date review of previous work, both experimental and theoretical, on the subject of superheating and super-
cooling in type I superconductors. (iii) The onset of the intermediate state in transverse field can be studied under conditions where the radius of the "cylinder" is comparable with the width of the normal superconducting phase boundary or the coherence length $\xi$.

Previous work of this nature has been undertaken by Maxwell and Lutes\textsuperscript{5} as well as Lutes\textsuperscript{6} who used a resistive method to study the transitions. A resistive method has also been used by Rothberg \textit{et al.}\textsuperscript{7} who studied the phase diagrams of tin whiskers as a function of strain. As the present detection method was an inductive one it is doubtful if the presence of structures such as a film with an extremely small cross section on the side of a cylinder with a larger cross section (as observed by Rothberg \textit{et al.}) would be detectable.

Because there were no electrical contacts to act as nucleation sites and because an inhomogeneous field was superposed on the homogeneous field to eliminate the ends of the whisker as nucleation sites, considerably more hysteresis was observed than in previous experiments on whiskers.\textsuperscript{5–7}

2. EXPERIMENTAL METHOD

Whiskers were grown by the "squeeze" method\textsuperscript{8} in which the whiskers grow by an extrusion mechanism from tin plate. After some months whiskers several millimetres long and 1–2 $\mu$ in diameter could be obtained. Whiskers were selected under a microscope, removed with a micromanipulator, and x rayed. A whisker was then laid in the groove formed by two parallel 15 $\mu$ wires which formed the secondary of a mutual inductance system. A loop of 30 $\mu$ wire was used as the primary. An inhomogeneous field parallel to the whisker was provided by two parallel 50 $\mu$ niobium wires placed near the middle of the whisker. A cross section of the sample holder is shown in Fig. 1. In all other respects the ac mutual inductance detection system, operating at 150 KHz, was identical to that used in Ref. 4.

Homogeneous fields parallel (±2º) and perpendicular (±2º) to the whisker were provided by a crossed pair of Helmholtz coils. By suitably combining the homogeneous and inhomogeneous parallel fields, the inhomogeneous field configuration shown in Fig. 1 could be obtained. The earth's field was canceled by external Helmholtz coils to better than 0.02 G.

The temperature near $T_c$ could be stabilized to better than 0.1 mK and was measured using a calibrated germanium thermometer.

After canceling the background signal using the zero suppress of the lock-in amplifier, the off-balance signal was plotted at fixed temperature as a function of the current (field) in either the Helmholtz coils or the niobium wires.

For both parallel and transverse fields hysteresis loops were obtained when the off-balance signal was plotted against the homogeneous magnetic