INJECTION OF ELECTRONS INTO He II FROM AN IMMERSED TUNGSTEN FILAMENT*

Glenn E. Spangler and Frank L. Hereford
Department of Physics, University of Virginia, Charlottesville, Virginia

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Tungsten filaments have been operated while immersed in He II at temperatures up to 2500°K, and electron currents as high as 0.5 μA have been produced in the superfluid, yielding densities of at least 10^9 negative ions/cm^3. The fluid in the vicinity of the filament remains quiescent under these conditions as a result of a stable vapor film which forms around the filament.

We have operated tungsten filaments of 3 and 5 μ diam in He II at temperatures up to 2500°K and have measured electron currents as high as 0.5 μA injected into the He II bath.

As a result of a stable vapor film which forms around a heated filament,[1-3] it is thermally insulated to a high degree from the bath. Filament temperatures in excess of 2000°K have been maintained in the experiments to be described with no escape of vapor from the film and with the He II at the vapor-liquid interface in a quiescent state. The electron current which can be injected into He II by this method is orders of magnitude greater than that which has been produced by ionizing radiation or by tunnel junctions.[4] We report here measurements of the I-V characteristics of a superfluid diode incorporating a tungsten filament and describe several unexpected features of the filament and diode operation.

The diode consisted of a straight 1.5-cm length of tungsten wire surrounded by a 2-cm-diam gold-plated cylindrical brass anode. Anode voltages up to 2600 V were employed, and the device was operated at fixed depths below the surface of the He II bath ranging from 1 to 5 cm (the range in which vapor-film formation is known to occur[3]). The I-V characteristics of the diodes were measured at a temperature of the He II bath of 1.3°K. Preliminary results were obtained, also, with the diodes in vacuum, but residual pressure of the order of 10^{-5} mm Hg caused rapid deterioration of the filaments as a result of ion bombardment and made it impossible to obtain complete current versus voltage curves. Results for a 5-μ-diam filament in He II are shown in Fig. 1.

The following observations can be made:

(1) The data can be fitted closely by straight lines for the lower range of voltages. There is evidence that the curves for different depths of the diode converge in the 800- to 1000-V region and thereafter rise more steeply. We are inclined to attribute this to gas amplification in the vapor film, although more information on the space charge in the film and on the maximum primary current available from the filament is required to substantiate this interpretation. The curves are quite different from those obtained[5] when α particles produce the collected ions, and the applied field competes against recombination in extracting electrons from the α-particle ion column.

(2) The limited data obtained for operation in vacuum (not shown) indicated currents approximately two orders of magnitude greater than those obtained in He II. Thus, the presence of He II clearly inhibits the collection of negative

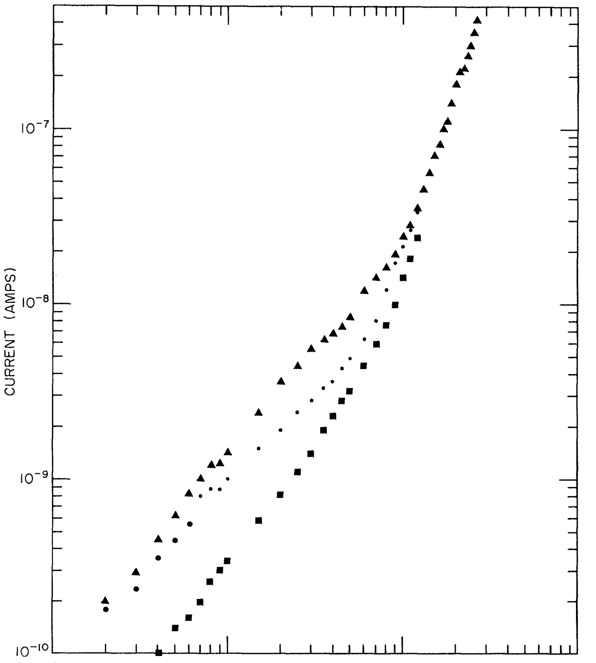

FIG. 1. Current versus voltage for a superfluid diode with a 5-μ-diam filament operated at the following values of filament power, temperature (±50°K), and depth, respectively: squares, 0.088 W, 2000°K, 3.0 cm; circles, 0.13 W, 2110°K, 3.0 cm; triangles, 0.13 W, 2160°K, 1.5 cm.

ions. We believe that the principal mechanism is a build up of space charge within the vapor film around the filament. The fact that the vapor-liquid interface represents a potential barrier of about 1 eV to the admission of electrons to the fluid[6] is probably a contributing factor.

(3) At a given voltage the current decreases (see Fig. 1) as the depth of the filament below the surface of the helium bath increases. It has not yet been possible to observe visually the cylindrical vapor film with the filament incandescent. However, previous studies in this laboratory[3] have demonstrated that as the depth of a heated wire increases, the critical heat current at which the vapor film forms also increases and the film's diameter after formation becomes smaller. Since the rate of transfer of heat from the filament to the bath should increase as the film diameter decreases, the filament should be cooler at greater depths and emit fewer electrons. We have been unable to confirm this behavior because of lack of precision in our pyrometer measurements of filament temperature (±50°K). At depths greater than 5 cm the filaments broke quickly when heated to incandescence, possibly as a result of vibrations. Previous observations[3] have shown that at large depths supercritical heating leads to some form of visible turbulence near the filament rather than formation of a stable vapor film.

(4) The vapor film is a surprisingly good thermal insulator. In the case of a 3-μ-diam filament, for example, a temperature of 1650°K was obtained in vacuum at a filament power (I^2R) of 117 mW. When it was immersed in He II at a depth of 5 cm, 168 mW was required to obtain the same temperature. Hence, the He II bath was dissipating only 51 mW or approximately 30% of the total filament power, the remainder being radiated.

(5) Electron currents of the order of 0.5 μA were readily achieved with an emitting surface of pure tungsten of only 5×10^{-3} cm^2 and a collecting voltage of 2600 V. We intend to explore the use of larger surface areas and oxide-coated cathodes in an effort to produce significantly greater electron currents.

(6) The relation between the current I and the electron density n in the conducting region of the He II bath, for a filament of length l, is

$$I=2\pi rlen\mu E(r),$$

where μ and $E(r)$ are the negative-ion mobility and the electric field. If one neglects the field dependence of μ and all space-charge effects, the electron density can be estimated. Using the zero-field mobility data of Reif and Meyer,[7] one finds that a current of 0.5 μA implies an electron density of approximately 10^9 electrons/cm^3 (independent of the radius).

However, the mobility is strongly field dependent, and space-charge effects are undoubtedly substantial. There can be little doubt that near the electron-emitting vapor film (radius of approximately 0.01 cm) the field exceeds the critical value for ionic production and capture of vortex rings[8] (approximately 500 V/cm at 0.98°K). Hence, at least in this region the high field should effectively immobilize the negative ions (charged vortex rings) and reduce their drift velocity to the order of 100 cm/sec.[8] These circumstances would yield a negative-ion density at small radii much larger than 10^9 electrons/cm^3.

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