Memory device employing hysteretic properties of a tungsten filament in superfluid helium-4

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Abstract. A tungsten filament immersed in superfluid helium has strong hysteretic I-V characteristics. By increasing the applied voltage, a remarkable current drop occurs at a transition voltage, at which the filament enters a non-ohmic hot state and becomes covered with a helium gas sheath. The return to an ohmic state occurs at a lower voltage because of the poor heat conduction of the gas sheath. Hence, the I-V characteristic is strongly hysteretic. The stable hysteresis window was employed to fabricate a novel memory device, which demonstrated fast switching and stable reading.

Keywords: Memory device, resistance hysteresis, superfluid helium, first order transition

1. Introduction

Hysteresis is essential to the operation of memory devices.¹ ² In recent decades, a number of novel mechanisms of hysteresis have been explored to realize new memory devices.³ ⁴ An extremely strong nonlinear electric transport by a tungsten filament immersed in superfluid helium-4 (⁴He) was reported by Date et al. some time ago.⁵ They observed hysteresis in the I-V characteristics. The phenomenon was attributed to the formation of a He gas sheath surrounding the filament. The gas sheath is difficult to produce because of the high thermal conductivity of superfluid helium,⁶ but once formed it is difficult to collapse because of the poor thermal conductivity of the gas sheath. Actually, a glowing tungsten filament inside superfluid helium is one of the most popular demonstrations of superfluid helium. The filament glows as if it were in a vacuum. The liquid does not boil around the filament because the heat produced by the filament is immediately transported to a free surface and lost via evaporation. Paradoxically, however, because the thermal conductivity of a superfluid is infinitely high, the filament is cooled so efficiently that it is difficult to increase the temperature sufficiently for it to start glowing. This is resolved by the formation of a gas sheath wrapped around the filament.⁷ ⁸ ⁹
To understand the threshold of gas sheath formation and hysteresis, it is useful to know some basic properties of superfluid He. First, it has a high thermal conductivity because the heat is transported by the dynamic fluid flow in superfluid $^4$He instead of the usual diffusion. A superfluid consists of a macroscopic quantum condensate and an ensemble of thermally excited elementary excitations, namely phonons and rotons. The condensate is in the macroscopic quantum ground state and hence, carry no entropy, whereas the elementary excitations carry entropy and heat. The hydrodynamic motion of the condensate is characterized by the velocity field, $v_s$, and its density $\rho_s$, and referred to as a superfluid component. The ensemble of elementary excitations in the condensate acts like a normal fluid. Its density is defined by $\rho_n = \rho - \rho_s$ and the flow field is $v_n$, where $\rho$ is the total density of liquid helium. The total flux of the flow is $j = \rho_s v_s + \rho_n v_n$. This formulation is due to Landau’s two-fluid model.\cite{10} The heat flux $q$ is then given by

$$q = \rho_s T v_n,$$

(1)

where $s$ is the entropy per unit mass and $T$ is temperature. The thermal conductivity is limited by the effective friction force between the two fluids. It is understood that the friction is mediated by quantized vortex filaments in the superfluid component.\cite{11} In practice, the thermal conductivity of superfluid helium can be regarded as infinite. In this regime, the superfluid $^4$He touches the filament surface and the heat produced is efficiently removed from the filament, so that the filament stays cold and its temperature is uniform along its axis.

As more heat is produced, however, a gas sheath may appear. This occurs when the superfluidity is destroyed either by hitting a liquid–vapor phase boundary in the phase diagram of $^4$He (Refs. \cite{5} and \cite{8}) or because other critical conditions are exceeded. Accordingly, we should expect a transition from the cold state ($C$-state), where the superfluid is attached to the filament, to the hot state ($H$-state), in which the filament is covered by the gas sheath. Schematic drawings of the $C$- and $H$-states, which are associated with hysteresis, are shown in Figs. 1(a) and 1(b). These two states are distinguished by their different filament resistance values. This transition gives rise to the hysteretic transport properties of the tungsten filament in superfluid $^4$He. In this study, we experimentally explored the electric characteristics of a tungsten filament in superfluid $^4$He and utilized its hysteresis in the current versus voltage ($I$-$V$) characteristics to realize a memory device. This work must open a new research frontier in nano superfluidics and nano scale gas-liquid phase transitions.

Figure 1: (a) Schematic for the cold state of the filament in superfluid helium. (b) Schematic for the hot state of the filament covered with helium gas sheath in superfluid helium.
Figure 2: (a) SEM image of a coiled tungsten filament (sample F-01). (b) Magnified SEM image of tungsten wire (sample F-01).

Table 1: Sizes of tungsten filament samples.

| Filament type | Model number | Diameter (µm) | Length (mm) | Coil radius (µm) | Surface area (mm²) |
|---------------|--------------|---------------|-------------|------------------|--------------------|
| F-01          | 2012-00      | 3.97 ± 0.03   | 3.06 ± 0.07 | 12.26 ± 0.49     | 0.0382 ± 0.0008    |
| F-02          | 4032-00      | 9.57 ± 0.13   | 4.27 ± 0.12 | 24.59 ± 0.45     | 0.1284 ± 0.0053    |

2. Experimental methods

The filaments were prepared by removing the glass covers from miniature light bulbs (Micro-Glühlampen-Gesellschaft, Hamburg, Germany). Figures 2(a) and 2(b) show scanning electron microscope (SEM; JEOL IT-300) images of a typical filament (sample F-01), which was coiled and anchored at two metal electrodes. To determine the geometrical parameters of the two types of filament, we obtained SEM images of several filament samples from the same batch. The average radius of the filament wire and the diameter of the coil were measured. The total length of the filament was calculated from the number of coil turns and the length of the uncoiled part of the filament at both ends. The average total surface area of the filament was estimated from these size parameters. The surface area of two types of filament were measured and listed in Table 1.

The I-V characteristics were studied with four-wire measurements using a Keithley 2400 source meter. The voltage was swept in a 0.002 V step with a waiting time of 100 ms for each step. The experimental setup consisted of liquid helium in a cylindrical glass Dewar surrounded by liquid nitrogen. The temperature was controlled by regulating the saturated vapor pressure of the liquid helium. The measurements were performed in a temperature range below the superfluid transition temperature $T_\lambda$ (2.1768 K) of liquid $^4$He.

3. Results and discussion

Figure 3 shows the I-V characteristics of the tungsten filament (sample F-01) with forward and backward sweeps between 0 and 0.4 V at 1.86 K. The transition voltage ($V_t$) and critical voltage ($V_c$) divide the behavior into three regions. In the low-power and intermediate regions I and II of the forward sweep, the filament shows linear ohmic behavior. The resistance
Figure 3: Current versus voltage ($I$-$V$) characteristics of a tungsten filament (sample F-01) in superfluid helium. The red line indicates the forward sweep of the voltage from 0 to 0.4 V, and the black open circles indicate the backward sweep of the voltage from 0.4 to 0 V. $V_t$ is the transition voltage in the forward sweep at which the filament forms a sheath and enters the $H$-state. $V_c$ is the critical voltage at which the filament cools down and enters the ohmic $C$-state. The inset shows the $I$-$V$ characteristics of the tungsten filament in the vapor phase. A red line is a linear fitting in the low voltage region.

of the filament within these regions is almost constant at about $1.8 \, \Omega$, corresponding to the filament temperature. Due to the high thermal conductivity of a superfluid, the filament is unable to warm up before reaching $V_t = 0.146$ V. In contrast, for a tungsten filament placed over liquid He in the vapor phase, the $I$-$V$ characteristics are linear only below 0.02 V (inset of Fig. 3), which is much lower than $V_t$. At the transition voltage, a sheath of helium gas immediately forms along the filament. The sheath is a good thermal insulation layer, resulting in an abrupt increase of the filament temperature and resistance. In the high-power region III, the temperature and resistance of the filament further increase efficiently as the voltage increases. Note that the heating process has a differential negative resistance.\[12\]

In the backward sweep, the device cools as the bias voltage decreases. The filament is in the $H$-state in regions III and II of the backward sweep due to the gas sheath. As the voltage decreases, the sheath shrinks smoothly and eventually disappears at $V_c = 0.052$ V. At voltages below $V_c$, the filament returns to an ohmic state. In regions I and III, the $I$-$V$ characteristics of the backward sweep completely overlap those of the forward sweep. The difference between the state transition voltages for the forward and backward sweeps results in strong hysteresis in region II. The hysteresis window is defined as the difference between $V_t$ and $V_c$, which is about 0.094 V. The hysteresis loop is stable and reproducible if the environment temperature stays constant. The hysteresis loop has a promising potential for memory applications.

The relation between the heat conducted to the liquid and the heat flux produced by the filament is important. As the voltage increases beyond $V_t$, the superfluid $^4$He near the filament cannot sustain the direct contact with the filament surface. A sheath forms due to
rapid nucleation. Once a vapor bubble emerges in some area of the filament surface, the temperature of this area will immediately increase because of the low thermal conductivity of helium vapor. Then, the vapor bubble will rapidly expand to cover the whole filament. Unlike a hot filament in a normal liquid, which boils hard, in superfluid He, the filament is surrounded by a stable sheath and there is no boiling bubble. Helium gas inside the sheath transports heat from the surface of the filament to the liquid.

The heat flux density plays an important role in the transition from the C- to the H-state and the hysteresis. A superfluid component carries neither entropy nor viscosity. Therefore, only the normal component is associated with the heat flux [Eq. (1)]. We observed that the transition voltage, \( V_t \), is temperature dependent. As the temperature decreases, the transition voltage appears and increases. It saturates at about 0.14 V below a temperature of 1.86 K. Our observations are qualitatively consistent with previous reports.[8, 5, 13] Note, however, that the critical heat flux densities found are larger than in the previous work.

To investigate the effect of heat flux density, two different types of filament with different diameters were investigated, F-01 and F-02. Figure 4(a) shows the I-V characteristics for the two different samples at 1.744 K. The thicker filament sample, F-02, also has a transition. In the ohmic state region, owing to the ratio of the total length and cross-sectional area, the sample F-02 has a lower resistance of 0.29 \( \Omega \) compared with sample F-01. The heat flux density as a function of the voltage of the tungsten filaments is shown in Fig. 4(b). Although the critical currents shown in Fig. 4(a) differ, the critical heat flux densities are close to each other, as shown in Fig. 4(b). The transition heat flux densities of samples F-01 and F-02 were 0.316 W/mm\(^2\) (31.6 W/cm\(^2\)) and 0.208 W/mm\(^2\) (20.8 W/cm\(^2\)), respectively. These values are an order of magnitude larger than the previously reported values. We attribute this difference to the preparation of the samples. The formerly reported values were obtained by employing either Nichrome or tungsten wire manually fixed to the sample cell. Our tungsten filaments were from commercial light bulbs. The glass was broken immediately before the experiment, so that the surfaces should have been fresh and relatively uncontaminated. Note that the first voltage scan after a filament was immersed in liquid helium had unreplicable irregularities, steps, or spikes. The trace became stable and reproducible only after the first sweep.[5]

From the critical heat flux density of both samples, the velocities of the normal fluid and the superfluid component can be calculated using Eq. (1). \( v_n \) and \( v_s \) of sample F-01 (F-02) were 2.70 (1.80) and 0.98 (0.65) m/s. The critical relative counterflow velocities, \( |v_n - v_s| \), for F-01 and F-02 were 3.68 and 2.45 m/s, respectively, at 1.744 K. Note that the critical velocity obtained is much larger than the usual critical velocity for quantum turbulence.[14, 15, 16, 17, 18]

These large critical values are essential for realizing a stable and wide hysteresis window. Moreover, we observed no depth dependence, which had been reported previously.[8, 5] The details of these critical behaviors will be discussed elsewhere.

A memory device is a particularly interesting application of a filament in superfluid \(^4\)He. There are two memory states within the hysteresis window, which can be utilized as program and erase states, respectively. The hysteresis window is large enough to define the read voltage for a memory device. Therefore, we demonstrated the memory functionality with a filament
Figure 4: (a) $I$-$V$ characteristics of tungsten filaments, F-01 and F-02 (Table 1), with different diameters in superfluid helium. (b) Heat flux density emitted from the filaments as a function of voltage. $T = 1.744$ K.

Figure 5: (a) Current stability of program and erase states of a filament (sample F-01) during 300 s of hold time. The reading voltage was 0.1 V, and programming and erasing were done at 0.2 V for 100 ms duration and at 0 V for 100 ms duration, respectively. (b) Reproducible memory operation with 3 s hold time for the same reading and programming conditions as in (a).

via the same measurement setup.

First, the program and erase voltages were chosen as 0.2 V and 0 V, respectively. The read voltage was defined as 0.1 V in the middle of the hysteresis window. In Fig. 5(a), to elucidate the retention ability of the memory device, program and erase pulses of duration 100 ms were applied to filament F-01. Because the erase state occurs before the formation of the sheath, the mechanism for reading the current is due to ohmic behavior, which is proportional to the read voltage. After applying a pulse of 0.2 V, the filament became surrounded by a sheath at the same read voltage, which is defined as the program state. The filament is hot in the program state, and the current is remarkably stable. We measured the current of the two memory states with a read voltage for at least 300 s. As a result of the stability of both states, the current ratio was maintained at about 2.3 for at least 300 s. Notice that our device can switch states without any charge time, which is usually observed in a charge-trap memory device. [19, 20] The memory device was dynamically switched between the program and erase states by repeating the erase or program pulse, as shown in Fig. 5(b). After 10 cycles of programming and erasing, the two states were still stable, which indicates the reproducibility and endurance of this memory device.
In addition to the reproducibility and endurance, the writing speed is another measure of the performance of a memory device. In a speed test, however, the time resolution of a four-wire measurement is limited by the source meter, which is only about 100 ms. To determine the shortest pulse width of the program and erase processes, we employed a function generator (Agilent, 33220a) and an oscilloscope (Teledyne Lecroy, HDO4034) to measure the dynamic response of the memory. The experimental setup is shown in Fig. A1(a) in the Appendix. The two-wire hysteresis loop in Fig. A1(b) in the Appendix is different from that for the four-wire measurement because of the in-series contact and wire resistance. Thus, the program, erase, and read voltages were defined to be 0.5, 0, and 0.25 V, respectively. The dynamic responses of the shortest pulse for each process are presented in Figs. A1(c) and (d) in the Appendix. The program and erase processes are attributed to different switching mechanisms, that is, sheath nucleation and filament cooling. Therefore, the transition time for programming (300 µs) is shorter than for erasing (10 ms). The shortest pulse for the program and erase states are faster than is usual for a dielectric oxide memory device made from 2D materials. [19, 20, 21]

4. Summary and conclusion

In summary, the results presented in this paper show that a dramatic current drop is observed during voltage sweeping of a tungsten filament in superfluid $^4$He. The $C$- and the $H$-states can be determined from the different voltage bias regions. The state transitions are due to the formation and annihilation of a helium gas sheath. The state transitions in the forward and backward sweeps occur at the transition voltage $V_t$ and critical voltage $V_c$, respectively. During the voltage sweeping, there is a hysteresis window of about 0.094 V due to the difference between $V_t$ and $V_c$. It is suggested that the formation of the sheath depends on a critical power density. The first-order phase transition occurs at the critical heat flux from the filament surface. By defining program, erase, and read voltages at 0.2, 0, and 0.1 V, respectively, we demonstrated the operation of a stable memory device with two states. The memory device had a strong retention ability, as the current for both states can remain constant for at least 300 s. Good reproducibility and endurance were observed by dynamically switching between the program and erase states. Our results confirm that the heating and cooling of a filament produce a stable hysteresis loop in superfluid $^4$He. A memory device was realized, demonstrating the promising potential of semiconducting nanowires.

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Figure A1: (a) Diagram of the setup for measuring the dynamic behavior. (b) Current versus voltage \((I-V)\) characteristics of a tungsten filament (sample F-01) recorded by two-wire measurements. (c) Dynamic response of programming with a pulse of 0.5 V for 300 µs. (d) Dynamic response of the erase process with a pulse of 0 V for 10 ms.

Appendix A. Dynamic behavior of the memory effect

To explore the transition speed of the program and erase states, we investigated the dynamic behavior of a filament using two-wire current measurements, as shown in Fig. A1(a). A function generator (Agilent, 33220a) provided signals with different pulse widths. A voltage follower was connected to buffer the output signal because the filament impedance is much smaller than 50 Ω. The output was applied to the filament sample, and the current generated was registered by a current-sense amplifier. An oscilloscope (Teledyne Lecroy, HDO4034) was used to record the current signal. Due to the in-series contact and wire resistance, the hysteresis loop in two-wire measurements is different from that in four-wire measurements, as described in the main text.

Figure A1(b) shows the \(I-V\) characteristics of the tungsten filament (sample F-01) recorded by two-wire measurements. The transition voltage and critical voltage are 0.35 V and 0.16 V, respectively. Hence, to demonstrate the memory behavior in the two-wire measurements, we defined the program, erase, and read voltages to be 0.5, 0, and 0.25 V, respectively. Figure A1(c) shows the dynamic response of the program process. The reading current was switched from the cold state (C-state) to the hot state (H-state) by a program pulse of 0.5 V in height and 300 µs in duration. In our observations, the speed limit of sheath formation is about 300 µs, which is related to the time constant of nucleation. To transition the memory from the erase to the program state, the program pulse of a filament memory device must be equal to or greater than 300 µs. On the other hand, Fig. A1(d) presents the shortest response time of the dynamic erase process for a pre-programed device. The reading current
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was switched from the $H$-state to the $C$-state by an erase pulse with a 0 V output voltage for 10 ms. This indicates that the cooling for the erase state takes about 10 ms. Hence, the operating speed of a filament memory device is limited by the cooling of the erase process.

Conflicts of interest

The authors declare no conflict of interest

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