Microfluidic Chambers for Studies of Confined Superfluid He-3

Abstract:

We have studied superfluid \(^3\)He confined to submicron slab geometries inside nanofabricated, microfluidic chambers. Two separate techniques were used; nuclear magnetic resonance (NMR) and the torsional oscillator (TO). NMR studies have shown a significant modification to the superfluid \(^3\)He phase diagram as a result of the confinement. However, the NMR sample chamber suffers from significant distortion under increasing pressure. The TO studies have observed a decoupling of the \(^3\)He in the normal state, thus preventing study of the superfluid state so far. Our current work has been focused on fabricating new NMR and TO cells to overcome their respective problems.

Summary of Research:

The order parameter of superfluid \(^3\)He is suppressed at a boundary and recovers over a length scale on the order of the coherence length, \(\xi\). The coherence length is pressure and temperature dependent, varying from 78 nm to \~15\ nm between 0.0 and 34 bar at \(T = 0.0\). When a sample of superfluid \(^3\)He is confined to a slab geometry, of thickness on the order of \(\xi\), the phase diagram is predicted to be modified from that of bulk liquid, and previously unobserved order parameters may also be stabilized [1].

Our original NMR cell consisted of a 10 mm \(\times\) 7 mm rectangular chamber and the TO cell consisted of a 10 mm outer diameter, 4 mm inner diameter circular chamber [2]. The chamber height for both cells was \(d = 640\) nm (\(d/\xi \approx 8.3\) at \(p = 0, T = 0\)). The chambers were etched into a 3 mm thick piece of and then sealed by anodic bonding of a 3 mm thick piece of Hoya SD-2 glass to the silicon. Thick pieces of silicon and glass were used to allow pressure tuning of the effective confinement, \(d/\xi\), while minimizing distortion of the cells.

The NMR experiments, carried out at Royal Holloway University, revealed a significant modification of the bulk phase diagram [3] and a hysteretic transition to an unidentified superfluid phase was also observed [4]. However, despite the use of the 3 mm thick silicon and glass, subsequent optical characterization of the NMR cell revealed significant distortion under pressure, on the order of 25 nm/bar at the center of the cell. Therefore a new cell design is required in order to reduce the cell distortion under pressure.

Increasing the thickness of the silicon and glass is not an option, since this will reduce the filling factor of the \(^3\)He sample inside the NMR receiver coil. Therefore a supporting structure is required to
reduce the distortion. The new design (see Figure 1) includes a 1 mm thick wall down the center of the cell, to which the glass will also be bonded. The chamber height of the new cells will also be increased to 1 µm, so as to increase \( d/\xi \) at zero pressure and place us closer to the domain of a new superfluid phase that is predicted to exhibit broken translational symmetry [1].

The TO experiments, carried out at Cornell, observed complete decoupling of the normal \(^3\)He from the oscillator below 100 mK [5], thus preventing a study of the superfluid state. Based on scans of the glass and silicon by atomic force microscopy (see Figure 2) and the analysis [6] of similar observations in a silver TO cell, we believe that the decoupling of the normal fluid was a result of the very low surface roughness of the silicon and glass.

Therefore we are currently working on producing new TO cells in which the silicon surface is controllably roughened. The method we are using involves evaporating a very thin film (nominally 1-2 nm) of gold onto the silicon. Such a film is not continuous, but instead consists of many small islands of gold, tens of nm in diameter. The gold islands can then be used as a mask for a reactive ion etch (RIE), thus patterning the silicon with an array of tiny nanopillars. Following the RIE, the gold is removed by wet etching.

Figure 3 shows a silicon surface patterned with a nominally 1.2 nm thick gold film and then etched with \( \text{CF}_4 \) plasma. The diameters of the gold islands range from about 10 to 40 nm and the etch depth (i.e. pillar height) was measured to be 11 nm by placing a witness sample inside the etcher. Calculations by Priya Sharma at Royal Holloway, have shown that such a surface should keep the normal fluid locked to the oscillator well below the superfluid transition, thus enabling a study of the superfluid state.

Distortion of the TO cells is not such a concern, since the width of the un-bonded area is much less than that of the NMR cell, but the chamber height of the new TO cells has also been increased to 1 µm for the same reason as described above for the NMR cells.

**References:**


**Figure 2:** Atomic force micrograph of the glass surface. Fits to the height distribution data and the surface autocorrelation function give a surface roughness of 0.85 nm and a correlation length of 73 nm.

**Figure 3:** Scanning electron micrograph of a silicon surface patterned as described in the text. The image was taken before the gold was removed to improve contrast.