# Study of dynamical properties of superfluid $^3$He film flow by inter-digitated capacitors

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**Abstract**

We have developed a new technique to study film flow of adsorbed superfluid $^3$He. By this technique utilizing inter-digitated capacitors, flow rate and thickness of the film can be controlled. We measured superfluid critical temperatures of film, $T_c^f$ , for thicknesses from 0.2 to 7.5 $\mu$m. The observed suppression of $T_c^f$ is consistent with the theoretical results of Fetter *et al*. and Kjäldman *et al*.

*Key words:* $^3$He superfluid,$^3$He superfluid film,film flow,size effect

In the geometry comparable to superfluid coherence length, superfluid $^3$He shows different properties from those of bulk. There are interesting theoretical suggestions such as stabilization of A-phase even under saturated vapor pressure, and existence of planar-phase. In spite of pioneering experimental efforts[1][2], many interesting aspects, in particular, dynamical properties have been still left to study. This is partly because the motion of tiny amount of sample should be detected at ultra-low temperatures.

We employed an inter-digitated capacitor (IDC) as a new device to overcome this problem. Manipulation and detection of film flow had been done by using a pair of IDCs which is installed perpendicular to the bulk liquid surface (Fig. 1). The film thickness on the IDC can be controlled by applying DC voltage to the IDC. The amount of liquid $^3$He on the IDC can be known from its capacitance. When we induce flow from bulk to upper IDC (UIDC) by applying DC voltage $V_U$ , the $^3$He film accumulated on the lower IDC (LIDC) works as a channel, which connects the film on the UIDC to the bulk liquid. We can measure dynamical flow properties of superfluid $^3$He film as a function of film thickness.

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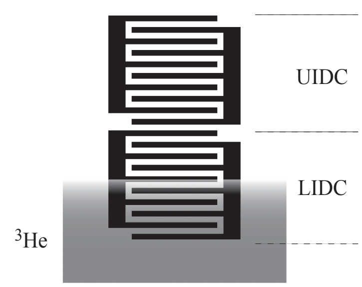


Fig. 1. A schematic view of a pair of inter-digitated capacitors (IDCs).

Each IDC consists of interlocking fingers of 2mm long, 10$\mu$m wide and separated by 10$\mu$m gaps. One side of IDC has 50 fingers. Totally, 200 fingers form two adjacent IDCs. This structure is made from a 300Å thick Au film deposited on a grass substrate(Corning 7059).

The film thickness on LIDC is determined by the balance between four kinds of effects: gravity, electrostatic field between the fingers, surface tension of liquid $^3$He, and van der Waals force between the substrate and $^3$He. The relation between DC voltage applied to the IDC and film thickness can be calculated by the model of Ref.[3] applied to the vertical case.

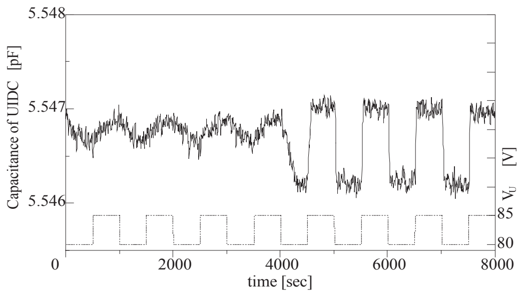


Fig. 2. The time evolution of capacitance is shown, where the critical temperature is crossed by cooling. The superfluid transition is observed as an abrupt change in the capacitance response (upper trace) to $V_U$ (lower trace). The film thickness is 2.0 $\mu$m.

The total capacitance of the UIDC is about 5.5 pF. The maximum manipulable amount of liquid $^3$He on the UIDC is ~0.4 mm$^3$, which corresponds to 0.04 pF capacitance change. It has the sensitivity to detect the change of $\sim 3{\times}10^{-5}$ mm$^3$ of liquid $^3$He.

We measured the thickness dependence of superfluid critical temperatures. By switching $V_U$ between 80 and 85 V every 500 seconds, accumulating and releasing liquid $^3$He are repeated, while the time evolution of capacitance of the UIDC is recorded. A typical result is shown in Fig. 2, where the thickness of the film on the LIDC is fixed to 2.0 $\mu$m. With decreasing temperature slowly, the transition from normal to superfluid is observed as an abrupt change in the response time of capacitance to the switched voltage.

The thickness dependence of superfluid critical temperatures of the film, $T_c^f$, normalized to the bulk critical temperature, $T_c^b$, is plotted in Fig. 3 by solid circle. For the thickness larger than about 0.7 $\mu$m, the transition occurs at temperatures close to $T_c^b$. For thinner films, suppression of $T_c^f$ is observed.

Since the free surface acts as a specular boundary, the effective thickness $D$ defined as the distance between two diffusive parallel plate, can be regard as twice of the present thickness $d$ (i.e. $D = 2d$) [2]. By using Ginzburg-Landau theory, the critical temperature for the slab with diffusive boundary is described as $D/\xi(T_c^f) = \pi$ [5], where $\xi(T)$ is temperature-dependent coherence length. This is represented by solid line in Fig.2. The other theoretical result by Kjäldman *et al.* is shown by the broken line, which is a numerical result valid for all the temperature range and thicknesses[6]. The agreement with these theories is good.

In conclusion, we developed a new technique to manipulate and measure the superfluid $^3$He film thickness. With this technique, we could carry out the experiment of superfluid $^3$He film for a wide range of thickness from 0.2 to 7.5$\mu$m. Since it is possible to measure dynamical properties such as superfluid critical current, further

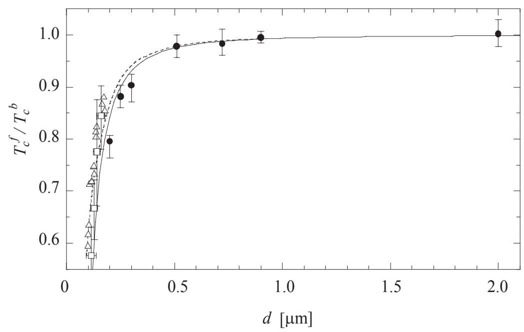


Fig. 3. The thickness dependence of critical temperatures. This work, Ref.[1] and Ref.[2] are shown by solid circle, triangle and square, respectively. Solid line and dashed line are theoretical results of Ref.[5] and Ref.[6].

experimental progress in $^3$He in confined geometry is expected.

## Acknowledgements

This work is partly supported by the Grant-in-Aid for Scientific Research from JSPS. One of the authors (MS) is gratefull to the JSPS fellowship.

## References

[1] J.Xu, B.C. Crooker, Phys. Rev. Lett. **65** (1990) 3005.

[2] S.C. Steel, J.P. Harrison, P. Zawadzki, A.Sachrajda, J, Low Temp. Phys. Rev. **95** (1994) 759.

[3] P. Roche, G. Deville, K.O. Keshishev, N.J. Appeyard, F.I.B. Williams, Phys. Rev. Lett. **75** (1995) 3316.

[4] Y.H. Li, T.L. Ho, Phys. Rev. B**38** (1988) 2362.

[5] A.L. Fetter, S. Ullah, J. Low Temp. Phys, **70** (1988) 515.

[6] L.H. Kjäldman, J. Kurkijärvi, D. Rainer, J. Low Temp. Phys, **33** (1978) 577.