Realizing highly coordinated, rapid and sustainable nucleate boiling in microchannels on HFE-7100

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1. Introduction

Compared to deionized (DI) water, properties of dielectric fluids are more stable and reliable for applications of electronics cooling [1–4], which make dielectric fluid flow boiling in microchannels a more favorable cooling solution for high power electronics. However, considering their unfavorable thermophysical properties, enhancing flow boiling heat transfer coefficient (HTC) and critical heat flux (CHF) in microchannels is a challenging task. For instance, the thermal conductivity of HFE-7100 is 0.069 W/m·K, approximately ~10 times lower than that of water (~0.6 W/m·K). Besides, the latent heat of vaporization of HFE-7100 is about 111.6 kJ/kg, nearly 20 times smaller than that of water. In addition, the surface tension is 13.6 mN/m at room temperature, about 5 times lower than that of water, making it difficult to form and sustain long thin liquid films on heating surfaces. Thus, it is challenging to promote efficient thin film evaporation and nucleate boiling.

Many efforts have been taken to enhance flow boiling HTC on dielectric fluids. For example, nanowires [3], reentrant cavities [4,5], porous graphite [6,7] and other porous surfaces [1] can effectively enhance nucleate boiling by increasing nucleation site density. In addition, sustaining thin film through enhanced capillary flows induced by micro/nano-structures can result in highly efficient thin film evaporation [5]. Other methods including diverging microchannels [8], inclining microchannels [9], and mixing generation [5] have been developed to significantly promote HTC on HFE-7100.

However, it is more challenging to enhance CHF of dielectric fluid flow boiling in microchannels. CHF crisis in a closed microchannel system can be triggered by three main factors, such as explosive boiling, two-phase flow instabilities, and local dry-out. The low thermal conductivity of dielectric fluids is more likely to create a highly desirable periodic rewetting mechanism to substantially delay CHF conditions and enhance heat transfer rate. Flow boiling in this innovative microchannel configuration has been systematically characterized with mass flux ranging from 462 kg/m²·s to 1617 kg/m²·s. Compared to plain-wall microchannels with inlet restrictors (IRs), flow boiling heat transfer coefficient (HTC) is enhanced up to ~172% at a mass flux of 462 kg/m²·s primarily owing to the enhanced latent heat transfer including nucleate boiling and thin film evaporation. The peak value of effective HTC is ~60 kW/m²·K in the fully developed boiling regime. Moreover, CHF is substantially enhanced by ~76% at a mass flux of 1155 kg/m²·s owing to the rapid and periodic rewetting enabled by these micro-slots. Such drastic enhancements have been achieved without compromising two-phase pressure drop.
more pronounced near the outlet section. Enhancing CHF on dielectric fluids at room temperature is few. For instance, the enhancement of HTC in microchannels with nanowires [3], reentrant cavities [4] and nanowires [3]. As aforementioned, Lee et al. has reported a high CHF of 5550 kg/m2 s on pre-cooled HFE-7100 in microchannels with reentrant cavities [4] and nanowires [3]. As aforementioned, Lee et al. has reported a high CHF of ~700 W/cm2 at a high mass flux of 5550 kg/m2 s on pre-cooled HFE-7100 in microchannels with the inlet temperature of a ~30 °C [26]. In general, it is extremely challenging to enhance CHF on dielectric fluid boiling without precooling inlet temperature.

In this study, an innovative microchannel configuration has been developed to enhance flow boiling in terms of HTC and CHF on HFE-7100. In this design, five parallel microchannels are interconnected by 28 micro-slots (width: 20 μm, height: 250 μm) starting from the outlet with a pitch of 180 μm on each wall. More details about the dimensions of microdevice have been discussed in our previous study [28]. These micro-slots can serve as nucleation sites to greatly enhance nucleate boiling. Fig. 2 shows experimental setup and the test package module. The test setup consists of an optical imaging system, a data acquisition unit, and an open coolant loop. The working fluid of HFE-7100 is pumped by pressurized nitrogen (N2). All test processes are executed at room temperature ~19 °C and 1 ATM. Details of experimental setup were reported in our previous studies [5,27].

Fabrication of the microchannel device: Fig. 3 shows the detailed flow chart to fabricate the microfluidic device. First, a 1 ± 0.01 μm thick thermal oxide layer was grown on both side of p-type (1 0 0) silicon wafer to provide electric insulation for the micro heaters and serve as a hard mask for deep reactive ion etching (DRIE). A 1 ± 0.05 μm thick thin film micro-heater was fabricated through a lift-off process on the backside of the wafer. Silicon oxide serving as an etching mask was etched off using reactive ion etching (RIE). Then five parallel micro-channels were etched by DRIE. The depth of the channel is 250 ± 3 μm. The DRIE process also creates deep vertical sidewalls with a root mean square (RMS) roughness of ~300 nm. A Pyrex glass wafer was anodically bonded to the silicon substrate to seal the microfluidic device. The individual microchannel test chips (length 30 ± 0.005 mm; width 10 ± 0.005 mm; thickness 1 ± 0.005 mm) were cut from the wafer by a dice saw. More detailed microfabrication was elucidated in our previous study [28].

2. Design and experimental procedures

2.1. Design and microfabrication of interconnected microchannels

In plain-wall microchannels, it is challenging to enhance heat transfer performances of flow boiling due to a long waiting time of bubble nucleation and bubble departure time. To promote flow boiling heat transfer performance of HFE-7100, an innovative microchannel configuration is designed, as shown in Fig. 1. The tested microdevice consists of five parallel microchannels (W = 200 μm, H = 250 μm, L = 10 mm) interconnected by 28 micro-slots (width: 20 μm, height: 250 μm) starting from the outlet with a pitch of 180 μm on each wall. More details about the dimensions of microdevice have been discussed in our previous study [28]. These micro-slots can serve as nucleation sites to greatly enhance nucleate boiling. Fig. 2 shows experimental setup and the test package module. The test setup consists of an optical imaging system, a data acquisition unit, and an open coolant loop. The working fluid of HFE-7100 is pumped by pressurized nitrogen (N2). All test processes are executed at room temperature ~19 °C and 1 ATM. Details of experimental setup were reported in our previous studies [5,27].
2.2. Data reduction

In experiments, the input power was calculated by multiplying the DC voltage ($V$) with current ($I$). Then the effective heat flux was calculated after subtracting the heat loss, $Q_{\text{loss}}$, (pre-calibrated between the ambient environment and the test device) from the total input power, $P$, as follow,

$$q_{\text{eff}}^0 = \frac{P - Q_{\text{loss}}}{A}$$

(1)

where $A$ is the base heating area. Based on the pre-calibrated linear relationship between temperature and electrical resistance, the average temperature of the micro heater (on the backside of the device) was calculated as,

$$T_{\text{heater}} = K(R - R_0) + T_a$$

(2)

where $R_0$ is the resistance of the micro heater at ambient temperature $T_a$ and $K$ is the slope of pre-calibration. The average temperature on the bottom wall of microchannels was then derived as,

$$T_{\text{wall}} = T_{\text{heater}} - \frac{q_{\text{eff}}^0 t}{k_s}$$

(3)

where $t$ and $k_s$ are the substrate thickness, thermal conductivity of silicon, respectively.

The fin efficiency, $\eta_f$, of a finite fin was estimated from

$$\eta_f = \frac{T_{\text{wall}}}{T_{\text{heater}} - \frac{q_{\text{eff}}^0 t}{k_s}}$$

(4)

The equation of $\eta_f$ is used to characterize fin performance and to calculate the average effective HTC, where the parameter $m$ was calculated as,

$$m = \sqrt{2h(L + W)/k_sWL}$$

(5)

Then, the effective two-phase HTC considering fin efficiency, $h_{\text{tp}}$, is evaluated by,

$$h_{\text{tp}} = \frac{Q_{\text{latent}}}{\left(\sum (WL + 2HL\eta_f)(T_{\text{wall}} - T_{\text{sat}})\right)}$$

(6)

where $T_{\text{sat}}$ is the saturated temperature of working fluid. The latent heat contributed to boiling heat transfer was derived as,

$$Q_{\text{latent}} = P - Q_{\text{loss}} - Q_{\text{sensible}}$$

(7)

where $Q_{\text{sensible}}$ is the sensible heat due to the liquid temperature as follows.

$$Q_{\text{sensible}} = GAI(C_p(T_{\text{sat}} - T_i))$$

(8)
Major physical properties of dielectric fluid HFE-7100 are given in Table 1. $T_{sat}$ is a function of working pressure ($p$) in the middle of a microchannel.

The vapor quality was calculated as [28],

$$v = \frac{P_{eff}}{C_0 Q_{sensible} - m_{fg} (9)}$$

In addition, the overall heat transfer performance of the device was estimated as $h = \frac{P_{eff}}{A (T_{wall}/C_0 - T_{sat})}$.

### 2.3. Uncertainty analysis

The measurement uncertainties of flow rate, pressure, voltage, current, temperature, and microfabrication resolution are ±0.1%, ±1.5%, ±0.5%, ±0.5%, ±1 °C, and 3 μm, respectively [29]. And the uncertainties of bubble diameter and departure frequency are ±6% and ±7%, respectively, leading to an uncertainty of estimated heat flux contributions of ±20%. Uncertainty propagation is calculated using methods developed by Kline and McClintock [30]. The uncertainty of effective HTC has been estimated to be less than ±2 kW/m² K.

### 3. Results and discussion

#### 3.1. Flow boiling curves

In this study, the flow boiling performance in terms of effective HTC considering all effective heat transfer areas is characterized with mass flux ranging from 462 kg/m²s to 1617 kg/m²s. Fig. 4(a) shows that the effective HTCs decrease with the increase of heat flux. Fig. 4(b) shows the overall HTCs based on the heater area as a function of effective heat flux. The overall HTCs based on the heating area share almost the same trend with the effective HTCs, but ~2 times larger. An overall HTC of ~120 kW/m² K is achieved after the onset of nucleate boiling (ONB) at mass flux of 1155 kg/m²s. Fig. 4 also indicates that there are two distinct regimes of HTC curves. For mass flux ranging from 462 kg/m²s to 924 kg/m²s, the curves of HTC become flat after ONB. The sustainable nucleate boiling may contribute to the stable heat transfer rate. At mass flux of 1155 kg/m²s and 1617 kg/m²s, the HTCs gradually decline with the increase of heat flux. The high contribution of convection as well as occurrence of heating surface dry-out near outlet section should be two main reasons for the decrease of HTC, especially near CHF conditions.

#### 3.2. New nucleate boiling phenomena

##### 3.2.1. Bubble dynamics

A complete bubble dynamic cycle includes bubble growing time and bubble waiting time as schematically shown in Fig. 5. The bub-
The bubble growing time is the duration from bubble nucleation to departure or collapse on the heating surface. Additionally, the waiting time is the time of the initiation of nucleus on a nucleation site after previous bubble departure or collapse from the same site. The bubble departure frequency is defined by [31]:

\[ f_d = \frac{1}{t_w + t_g} \]  

(10)

Bubble dynamics in terms of bubble departure diameter \((D_d)\), bubble growth rate \((\frac{dD}{dt})\), bubble waiting and growth times are characterized and compared with those in plain-wall microchannels at different mass fluxes as shown in Fig. 6. Compared to those on the plain-wall microchannels, the bubble departure diameter \((D_d)\) and bubble growth rate \((\frac{dD}{dt})\) on the present microchannel configuration are \(~2.3\) times larger and \(~3\) times faster, respectively, as shown in Fig. 6(a, b). As depicted in Fig. 6(c and d), bubble waiting time \((t)\) on the present microchannel configuration is less than half of that on the plain-wall microchannels and the growing time of the present channel is \(~2.6\) times longer than that in plain-wall microchannels.

On highly wetting fluids, it would be challenging to meet two requirements for bubble nucleation on a plain wall: residual vapor and superheated fluid. The superior wetting liquids could completely occupy the nucleation sites by removing residual vapor after a bubble departure on the plain wall. Another factor, it would take longer time to make the refilled liquid in the nucleation site to be superheated. These two factors would lead to a significantly longer bubble waiting time. In contrast, in the interconnected microchannels with micro-slots, owing to the induced capillary pressure, a small amount of vapor could remain inside the micro-slots after the bubble departure. Moreover, liquid can be

![Fig. 5. Schematic of a bubble growth cycle including waiting and bubble growing periods for (a) interconnected microchannel configuration and (b) plain-wall microchannels.](image)

![Fig. 6. Comparisons of bubble dynamics between the present design and plain-wall microchannels at a mass flux of 693 kg/m²s. (a) Bubble departure diameter \((D_d)\) as a function of heat flux. (b) bubble diameter as a function of time and (c) bubble waiting time as a function of heat flux. (d) Bubble growing time as a function of heat flux.](image)
quickly sucked into the slots during the bubble departure process and heated up by walls after then, which keeps these micro-slots active all the time and greatly reduces the bubble waiting time as illustrated in Fig. 6(c and d). A visualization study has been conducted to validate these two hypotheses and are discussed in the next section.

Fig. 7 shows three sequential frames of liquid jetting from the micro-slots. These images are selected from image sequences at a sample rate of 7000 frames per second (fps). The observed liquid jetting should be pumped out primarily by bubble expansion inside the slot and assisted by pressure imbalance between the neighboring channels owing to unstable non-uniform distributions of two-phase flow [32]. More importantly, this jetting flows well validate the existence of residual vapor and liquid inside the slots, which can significantly shorten the bubble growing time.

For a comparison, Fig. 8 depicts the waiting period of nucleate boiling in plain-wall microchannels at a mass flux of 693 kg/m²s and a heat flux of 65 W/cm². The bubble departure frequency in the plain-wall microchannels is ~355 Hz as shown in Fig. 11(a), which is lower than ~452 Hz at similar working load of interconnected channels. Besides, the bubble departure diameter is ~45 µm, around 2.3 times smaller and waiting time of the plain wall microchannels is ~1.3 times longer than that in interconnected microchannels, as shown in Fig. 6(a) and (c). Fig. 8(a) and (d) clearly show that the bubble nucleation on the plain wall randomly occurs and the bubble departure frequency in the plain-wall microchannels is much lower than that of the present microchannels owing to the shorter bubble waiting time.

Fig. 7. Liquid jetting from these slots at 40 W/cm² and a mass flux of 462 kg/m² s. (a) Initial stage of non-fluid jetting status. (b, c) Fluid jetting observed in two sequential images.

Fig. 8. Waiting time in plain-wall microchannels at a mass flux of 693 kg/m²s and a heat flux of 65 W/cm². (a) Bubble departs from wall surface, (b, c) no bubble nucleation appears with a long waiting period, and (d) new bubble appears at same nucleation site.

Fig. 9. A bubble growth process at a mass flux of 462 kg/m² s and a heat flux of 40 W/cm². (a) Initial stage for interconnected channel, (b) bubble growing from micro-slots, (c) bubble collapsing or departing from channel, and (d) bubble merging together.

Fig. 9 shows the bubble growth process in the interconnected microchannels at a mass flux of 462 kg/m² s and a heat flux of 40 W/cm². Compared to the plain-wall microchannel, the bubble growth and departure or collapse in the interconnected channel has been harmonically coordinated. The bubble growing time is measured at ~220 µs as shown in Fig. 6(d).

Another parameter in characterizing bubble dynamics is active nucleation site density. The active nucleation site density was estimated by dividing the measured number of active nucleation sites to the total area using images captured by a high speed camera [33]. As shown in Fig. 10, the active nucleation site density of interconnected microchannels is a constant of 2240 sites/cm² owing to the 100% active nucleating sites, which is ~1.86 times higher than
the cavity structure at similar working condition of a mass flux 693 kg/m²s and 1.7 times higher than that of plain-wall microchannels.

The micro-slots in the interconnected channels were 100% activated during the boiling but reentry-cavities in our previous design were only 22.2% activated according to experiment data [5]. High active nucleation site density can facilitate efficient nucleate boiling heat transfer.

Fig. 11(a) shows the effects of mass flux and heat flux on bubble departure frequency, which increases with the increase of heat flux and decreases with the increase of mass flux on the present microchannel configuration. In addition, Fig. 11(c) demonstrates that the switching frequency increases as the heat flux increasing at different mass fluxes. The trends of bubble switch frequency were nearly overlapped in two different mass fluxes, meaning that it should be primarily determined by nucleate boiling. Bubble departure frequency and departure diameter are highly affected by the superheat. A reported study has suggested the bubble departure diameter is closely related to departure frequency in the form of $f D_d = \text{constant}$ [34]. In this study, a fit curve is $f D_d = 0.07$. It is obtained from curve-fitting experimental results in Fig. 11(b).

3.2.2. Coordinated nucleate boiling

In conventional microchannels, nucleate boiling in individual channel is usually isolated. It would be highly desirable to harmonically coordinate these usually isolated boiling processes to enhance nucleate boiling heat transfer. On the present microchannel configuration, bubble nucleation switches between two sides of each wall at a high frequency. More importantly, the bubble nucleation and departure process on one side of the wall can enhance nucleate boiling on the other side of the wall, which greatly enhances bubble nucleation. Thus, for the first time, nucleate boiling has been harmonically coordinated through these well designated micro-slots as illustrated in Fig. 12(a).

The bubble growth and switching between two neighboring channels has revealed in Fig. 12(a and b). In according to the visualization study, the bubble first nucleates on the upper surface of channel #1 and after the bubble collapse or departure, a bubble starts to nucleate and grow on the top surface of channel #2. Then the bubble nucleates on the bottom surface of channels #1 and #2, sequentially. This bubble switching period, $t_s$, is the duration between the bubble growth on the top surface of channel #1 and #2 to it occurs on the top surface of channel #1 and #2. The whole switching bubble nucleation process has been illustrated in Fig. 12(b). The bubble switching frequency is calculated by $f = 1/t_s$.

As illustrated in Fig. 12(c), the switching frequency increases smoothly with the heat flux increasing. As the mass flux increased at different working conditions, the switch frequency decreased at the same heat flux. For instance, the switch frequency at heat flux of 60 W/cm² at 462 kg/m²s is around 425 Hz, and for 693 kg/m²s is 410 Hz approximately.
3.3. Enhanced HTC

Compared to the plain-wall microchannel configuration, the effective HTCs by considering all effective heat transfer areas in this study are substantially enhanced, as shown in Fig. 13(a, b). Significant enhancements of ~175% and ~156% are achieved, respectively, at a mass flux of 462 kg/m²s and 693 kg/m²s. The enhanced mechanism of HTC is explored as following. On the plain wall surface, it is difficult to form large areas of thin liquid film due to the low surface tension of HFE-7100. The explosive boiling would possibly take place and blow off the liquid film from the heating surface, resulting in local dry-out spots. Meanwhile, the suppressed nucleate boiling due to the highly wetting ability of HFE-7100 would deteriorate heat transfer rates.

The interconnected microchannel configuration developed in this study can overcome these aforementioned challenges. Nucleate boiling has been drastically enhanced by increasing active nucleation site density and bubble growth/departure rates. The 28 micro-slots can serve as nucleation sites to greatly enhance nucleate boiling. More importantly, highly desirable periodic rewetting is enabled in each channel and coordinated between channels by these micro-slots.

Comparisons between the current design and the plain-wall microchannels at different mass fluxes were conducted as shown in Fig. 13. Two types of effects including heat flux and vapor quality were compared to indicate the heat transfer mechanism as shown in Fig. 13(c, d). The interconnected channels can enable significantly higher vapor quality (enhanced up to ~55% at a mass flux of 462 kg/m²s) than the plain-wall microchannels do. This is because the new microchannel configuration increases high nucleation-site-density and keeps them activated, which greatly enhances contributions of latent heat transfer as indicated by high exit vapor quality. Note that HTC remains stable as a function of the vapor quality.

During the coordinated nucleate boiling process, heat is primarily transferred by advection, nucleate boiling, and evaporation. To better understand the enhanced mechanisms, these three heat transfer modes have been analyzed. The advection heat flux \( q_{adv} = q_{total} - q_{nuc} - q_{eva} \) including mixing and convection contributions, which results from the disruption of the thermal boundary layer during bubble growth, lift-off and/or collapse [35]. The periodic disruption of thermal boundary layer can reduce the thermal resistance [36–40]. The nucleate boiling heat flux \( q_{nuc} = \rho_l h_{fg} N_{af} \) is defined as the amount of heat carried away by these bubbles nucleated on the heating surface. On the present microchannel configuration, the whole growth process of each individual bubble can be accurately measured by high spatiotemporal images captured by high-speed camera (Phantom v7.3) owing to the large bubble departure size, extended growth time, and fully activated sites as illustrated in Fig. 6. The evaporation heat flux can be estimated by excluding nucleate boiling from the total latent heat flux \( q_{eva} = \chi n h_{fg} A_{heater} - q_{nuc} \).

Fig. 13. Significant enhancements of HTC are achieved on the present design compared to plain wall microchannels. (a, b) Effective HTC as a function of effective heat flux. (c, d) Effective HTC as a function of vapor quality.
Fig. 14 summarizes the ratio of three major heat transfer mode contributions to the total effective heat flux at different mass fluxes between the two configurations. In the plain-wall microchannels, the advection heat transfer at a mass flux of 693 kg/m²s dominates heat transfer, where heat transferred by nucleate boiling and evaporation only accounts a small fraction. Fig. 14(a, b, c) shows the nucleate boiling contributes 20–40% of the total heat transfer rate in the overall heat transfer process; while evaporation accounts for 21–46% of total heat removal, more than doubled compared to these in plain-wall microchannels. In those testing conditions, the contribution of the latent heat has been substantially enhanced, which should be the primarily reason behind the drastically enhanced HTCs enabled by the present microchannel configuration.
3.4. Enhanced CHF with reduced pressure drop

Fig. 15 compares the enhanced CHF for mass flux ranging from 462 kg/m² s to 1617 kg/m² s in the present design with that of the plain-wall microchannels. A significant enhancement of ~76% has been achieved at a mass flux of 1155 kg/m² s by enhancing liquid supply and rewetting through the micro-slots. Moreover, a slight decrease of ~6% of two-phase pressure drop was found compared to the plain-wall microchannels (Fig. 15b).

The enhancement of CHF indicates that micro-slots play a vital role in enhancing CHF. The rapid and periodic rewetting enabled by the highly coordinated nucleate boiling in neighboring channels are the main factor leading to the enhanced CHF.

Usually, premature CHF conditions can be triggered by explosive boiling, flow instabilities, and partial dry-out. For plain-wall microchannels with IRs, when heat flux increases, explosive boiling is likely to occur because the low thermal conductivity of HFE-7100. Then, thin liquid film would be expelled away from walls and eventually, vapor layer forms on the heating surface because of its low surface tension. The integration of micro-slots has successfully prevented the occurrence of explosive boiling by.

Heating surface dry out is one of the main factors resulting in premature CHF conditions. Enhanced liquid spreading by increasing capillary flows is essential to increase CHF. Normally, surface rewetting is highly influenced by the properties of working fluid, surface conditions of heating surfaces and two-phase transport regimes. However, it is challenging to increase CHF on low surface tension HFE-7100. In conventional plain-wall microchannels, it is difficult to maintain liquid film on heating surface on HFE-7100 because of its low surface tension. The potential solution for this issue is to enhance capillary pressure through surface modification such as nanowires to compensate the low surface tension. Although local rewetting is enhanced in microchannel covered with nanowires, the global liquid supply greatly suffers from high flow resistance resulting from dense nanowires. As a result, the enhancement of CHF is not significant using nanowires. In this study, individual microchannel interconnected by micro-slots would greatly promote liquid rewetting. Fig. 16 shows that thin liquid film can be sustained between the micro-slots, effectively delaying local surface dry out at a mass flux of 462 kg/m² s and a heat flux of 44 W/cm² in the present study. The high frequency nucleation boiling in the present design can also improve liquid supply to the neighboring channels.

4. Conclusions

In this study, flow boiling of HFE-7100 has been systematically characterized on an innovative microchannel configuration. Rapid and sustainable nucleate boiling has been well coordinated through designated micro-slots for the first time. Compared to the plain-wall microchannels, HTC and CHF have been considerably enhanced without compromising two-phase pressure drop. The primary HTC enhancement mechanism is the higher contribution of latent heat transfer on the present microchannel configuration. The highly coordinated and high frequency nucleate boiling process also greatly delays CHF conditions. The bubble dynamics have been systematically characterized in terms of bubble growth rates, bubble departure diameter, and bubble departure frequency and explain enhanced nucleate boiling.

Acknowledgments

This work was supported by the U.S. Department of Defense, Office of Naval Research under the Grants N000141210724 and N000141612307 (Program Officer Dr. Mark Spector). Devices were
fabricated at Institute of Electronics and Nanotechnology (IEN) in Georgia Tech, which is supported by the National Science Foundation under the Grant ECS-0335765. SEM images were taken at USC Microscopy Center.

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