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## Water droplet dynamics on a heated nanowire surface

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When a liquid droplet is deposited onto a heated surface, evaporation occurs. If the temperature of the surface is sufficiently high, bubbles are released from activated nucleation sites, making the heat transfer more efficient. However, if the temperature of the surface is further increased above the Leidenfrost point, a vapour cushion will form underneath the droplet, deteriorating the heat transfer between the surface and the droplet. In this work, we show that patterned Si nanowires can allow shifting the Leidenfrost temperature while maintaining a minimum droplet evaporation lifetime. In particular, it is observed that the Leidenfrost point is reached when the phase-change time scale compared to the wicking time scale becomes dominant. In this situation, the energy of the lift-off process is not sufficient for allowing the droplet to reach a sufficient height from where the droplet can penetrate in the porous surface. *Published by AIP Publishing.*

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When a liquid droplet is deposited onto a heated surface, four very distinctive behaviours are observed depending on the wall superheat  $\Delta T_{sat} = T_s - T_{sat}$ , with  $T_s$  being the surface temperature and  $T_{sat}$  being the saturation temperature of the liquid as sketched in Fig. 1. Below saturation temperature, a single phase regime is observed and the heat is transferred by conduction from the wall to the liquid. At higher  $\Delta T_{sat}$ , the nucleate boiling regime is observed and small bubbles are formed inside the droplet. The heat transfer will increase until the formation of the bubbles is so rapid that a vapour blanket or film begins to form on the surface. In this regime, the nucleate and film boiling regime will coexist, but the fraction of film boiling to nucleate boiling will increase with increasing  $\Delta T_{sat}$ . Above a critical temperature referred to be Leidenfrost temperature, the film boiling regime commences and the drop is levitated by the formation of a thin vapour continuous cushion. The droplet hovers over the surface in a frictionless regime, and the cooling efficiency is reduced due to the low thermal conductivity of the vapour cushion. Delaying the Leidenfrost point (LFP) is crucial for the quenching of over-heated components as the cooling becomes ineffective and the temperature of the surface can reach dangerous levels for example in the case of the Fukushima disaster.<sup>1,2</sup> Furthermore, the Leidenfrost effect can obstruct the development of cooling technologies related to high-heat-flux applications.

A significant amount of research has been performed in the last decade on the effect of the micro-/nanosurface on the Leidenfrost phenomenon.<sup>3</sup> In particular, most research has been focused to shift the Leidenfrost temperature towards higher temperatures;<sup>2,4-9</sup> however, the role of surface structures at different length scales and the dominant mechanisms controlling the shift on the Leidenfrost temperature remain still a standing question. For example, the increase in the Leidenfrost temperature due to micro-pillars

was attributed to an increase in the capillary pressure.<sup>2</sup> But it has also been suggested that nano-porosity is important in increasing the LFP by initiating heterogeneous nucleation of bubbles during the short-lived solid-liquid contact which disrupts the vapour film.<sup>4</sup> On the other hand, in the case of nanotubes, the increase in the Leidenfrost temperature was attributed to the increase in the slip velocity<sup>5</sup> caused by the nanotubes that help the escape of vapour beneath the droplet which in turn reduces the possibility of forming a vapour cushion. Different mechanisms are suggested for decoupled hierarchical structures (a combination of nano-membranes and microstructures)<sup>8</sup> where it is attributed that the Leidenfrost temperature is controlled by a balance between the dewetting force by the vapour which is governed by the microstructure and the capillary force governed by the

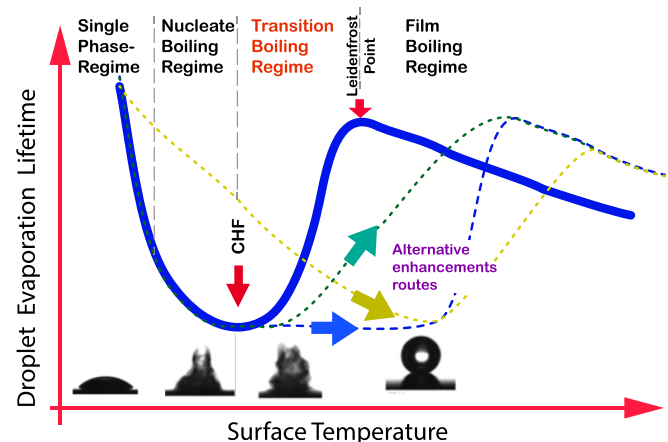


FIG. 1. Droplet evaporation lifetime and heat transfer regimes of the droplet over a heated surface. The dashed lines correspond to possible different trends of the sessile droplet evaporation observed in the experiments. The green curve represents a progressive deterioration of the cooling performance during transition boiling. The yellow one indicates a not efficient cooling performance despite the high shift in the LFP. The purple curve (observed in this work) represents an efficient transition boiling regime until the sudden occurrence of the LFP.

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nano-membrane. Hence, the dominant physical mechanism controlling the Leidenfrost temperature remains elusive although previous research has been able to identify different possible mechanisms for different types of surfaces.

Most research connected to increasing the Leidenfrost temperature has been motivated in improving the cooling performance of the surface. However, shifting the Leidenfrost temperature to higher values is not always connected to an improvement of the cooling performance of the droplet (as shown in Fig. 1). For example, by adding micro-nanostructures, a monotonous heat transfer deterioration can be observed from the minimum droplet evaporation lifetime.<sup>4</sup> While a decoupled hierarchical structure can shift the Leidenfrost point, the droplet lifetime at lower temperature is increased,<sup>10</sup> thus reducing the cooling performance at low temperatures. On the other hand, random Si nanowires have shown the possibility of shifting the Leidenfrost temperature while maintaining a low droplet lifetime during the transition boiling regime.<sup>9</sup> However, the random nature of the nano-channels within the nanowire carpet is responsible for a high solid fraction, thus hindering the vapour-escaping pathway and increasing the viscous resistance. In particular, it has been reported that aligned Si nanowire arrays can significantly enhance the critical heat flux compared to the random Si NWs in the case of pool boiling due to their higher wickability.<sup>11</sup>

In this letter, we show that pattern Si nanowires can allow the shifting of the Leidenfrost temperature to higher values while maintaining a minimum droplet evaporation lifetime.

The patterned nanowires with a diameter,  $d$ , of  $221 \pm 5$  nm, a height,  $h$ , of  $3.612 \pm 0.007 \mu\text{m}$ , and a pitch,  $p$ , of  $628 \pm 7$  nm were fabricated by using Metal Assisted Chemical Etching coupled with e-beam lithography. Figure 2 shows the SEM views of the patterned Si nanowires prior to the experiment (additional details concerning the method and characterization are provided in the [supplementary material](#)). The effect of surface texture on the droplet evaporation is investigated by depositing millimetric droplets ( $9 \mu\text{l}$ , deionized water) onto heated silicon surfaces textured (Fig. 2). For minimising inertial effects, the droplets are gently deposited ( $We \approx 2$ ). The Weber number is defined as  $We = \rho_L U^2 D / \sigma$ , where  $\rho_L$  is the density of liquid,  $U$  is the impinging velocity,  $D$  is the diameter of the droplet, and  $\sigma$  is the surface tension of the liquid. Figure 3 shows that the bare Si surface has almost no transient boiling region between the critical heat flux, CHF, i.e., minimum evaporation time, and the Leidenfrost point. On the other hand, the patterned Si NW surface shows a transition boiling of about  $120^\circ\text{C}$ . In these two cases, it is observed that the transition from the minimum of the droplet lifetime to the Leidenfrost point is quite abrupt.

The patterned surface shows an improved wettability (apparent contact angle of  $4^\circ$  compared to  $43^\circ$  of the bare

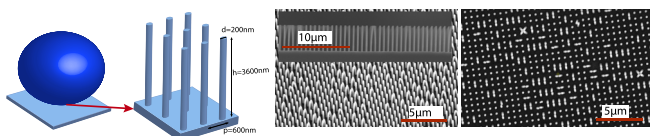


FIG. 2. Tilted SEM view of the Si patterned nanowires (tilt =  $20^\circ$ ) and top view. The subset shows a S(T)EM cross section of the nanowire array.

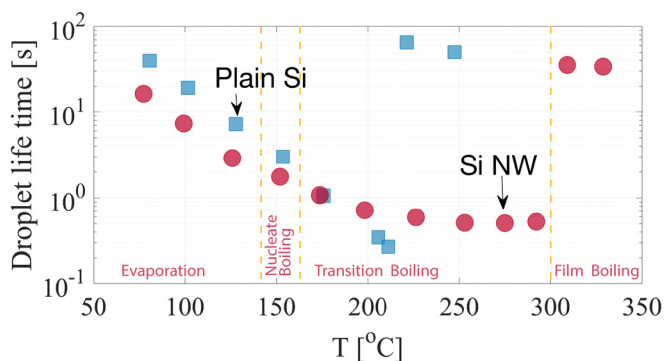


FIG. 3. Sessile droplet evaporation curve showing the evaporation time of a  $9 \mu\text{l}$  DI water droplet versus the surface temperature for both the plain Si and Si nanowires ( $We \approx 2$ ). The dashed lines identify the droplet dynamics on the nanowire surface.

surface) and liquid spreading phenomenon due to capillary suction in the nanostructure. Considering the case of the bare surface,<sup>12</sup> the radius of the spreading drop increases as  $(\rho g V^3 t / \nu)^{1/8}$ , where  $\rho$  is the liquid density,  $g$  the gravity force,  $V$  the volume of the droplet, and  $\nu$  the liquid kinematic viscosity. In the case of the patterned nanowires, the radius of the spreading drop<sup>13</sup> increases as  $[4\pi\sigma h^2 d t / (6\mu p^2)]^{1/2}$ , with  $\mu$  being the liquid dynamic viscosity, assuming that the height of the structure is comparable to the pitch. In this case, a droplet of  $9 \mu\text{l}$  will take about 40 s to reach a radius of spreading of 10 mm, while 2 orders of magnitude less for the patterned nanowires. At relatively low temperature, the spreading of the liquid on the surface can be dominant compared to the time scale of phase-change as it can be observed in Fig. 4. At  $79^\circ\text{C}$ , the liquid spreads significantly in the case of the patterned nanowires before the evaporation takes place and the diameter of the droplet shrinks. However, in the case of the bare surface, the spreading is much lower. At  $174^\circ\text{C}$ , we cannot notice a difference in the spreading of the liquid for the patterned nanowires or the bare surface as the time scale of phase-change becomes dominant, and thus, the liquid cannot spread faster than the evaporation process.

As the temperature of the bare surface increases up to  $211^\circ\text{C}$  (see Fig. 4), the droplet is fragmented by the strong bubble nucleation. Increasing the temperature of the surface further (see Fig. 5), the droplet on the bare surface is lifted up by a rapid vaporisation at a recoiling triple line<sup>14,15</sup> reaching the Leidenfrost state. However, on the surface with patterned nanowires, a liquid dispersal phenomenon due to capillary suction between the nanostructures is observed. This yields a strong vapour generation that results in the lift-off phenomenon previously observed on oxide Ti nanotubes<sup>5</sup> and random Si nanowires.<sup>9</sup>

Then, the droplet jumps and the droplet hits the surface again, repeating the cycle. As the temperature of the surface increases, the characteristic time for the vapour generation becomes comparable to the capillary suction and the height of the jump reached by the droplet reduces (see Fig. 6). In this regime, the droplet life time remains almost constant as the process is controlled by the cyclic droplet jumping. Then, at the Leidenfrost point, the vapour formation is too fast for allowing the capillary suction into the structure to occur and the jump of the droplet remains at a minimum.

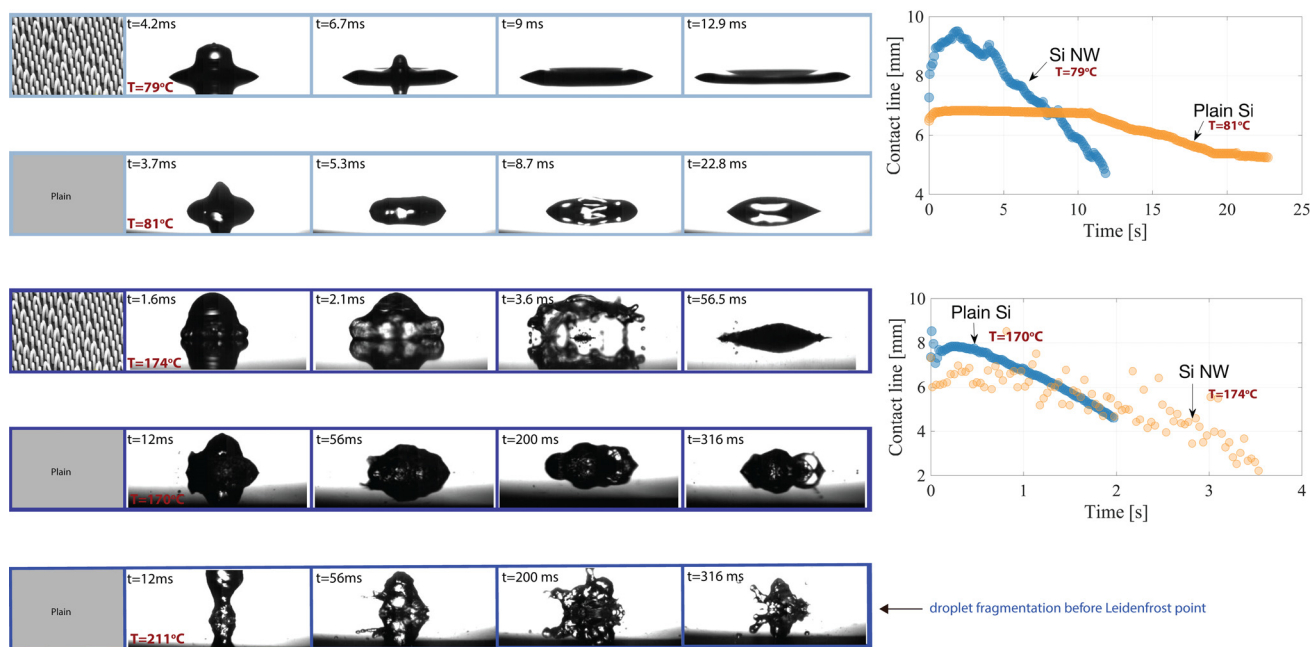


FIG. 4. Sessile droplet evaporation curve at low temperatures showing the evaporation time of a  $9 \mu\text{l}$  DI water droplet for both the plain Si and Si nanowires ( $We \approx 2$ ).

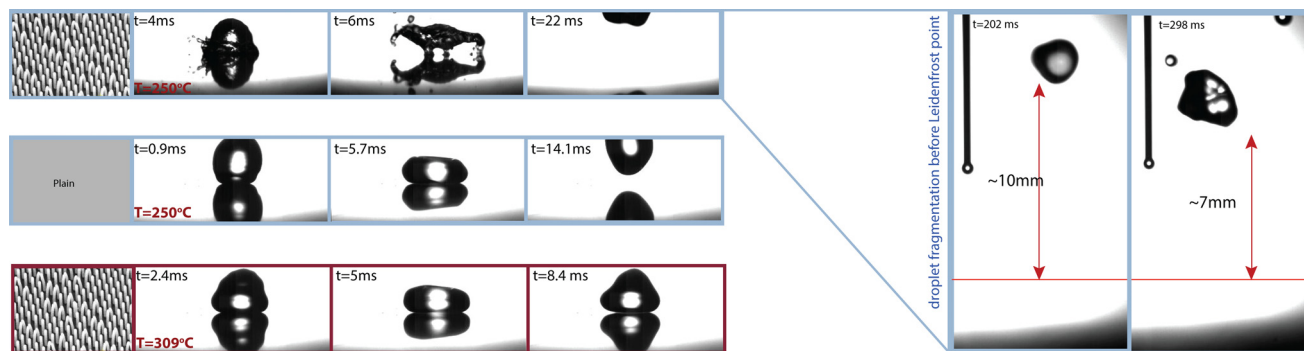


FIG. 5. Sessile droplet evaporation curve at high temperatures showing the evaporation time of a  $9 \mu\text{l}$  DI water droplet for both the plain Si and Si nanowires ( $We \approx 2$ ).

Assuming that the spreading is proportional to the height of the structure, the shift of the Leidenfrost temperature becomes proportional to the height of the nanostructures for equivalent structures. Figure 7 shows the shift on the Leidenfrost temperature as a function of the height of the nanostructures. However, above some critical height (close to  $8 \mu\text{m}$ ), no further improvement is observed in the increase in the Leidenfrost temperature. This effect can be attributed

to the saturation of the wicking with the height of the nano-wires,<sup>13</sup> i.e., the effect of increasing the nanowire height does not result in a further increase in the surface wickability. It has been reported that in the case of nanostructures, the wicking velocity will reach a maximum value as the height becomes too large compared to the other dimensions because of the increasing viscous force.<sup>16</sup>

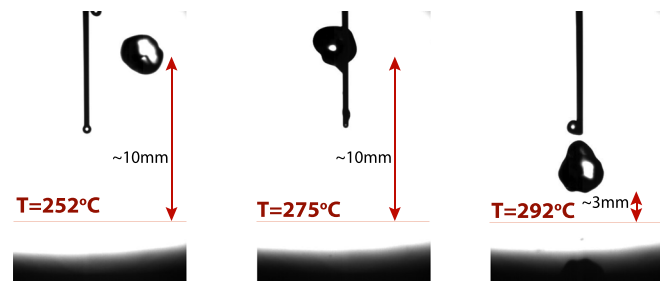


FIG. 6. Droplet jumping as a function of the surface temperature on the nanowire surface.

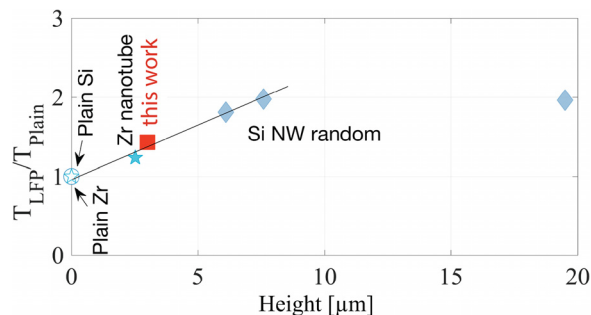


FIG. 7. Effect of the height of the nano-structure on the Leidenfrost temperature for Zr nanotubes<sup>5</sup> and Si random nanowires.<sup>9</sup>



In summary, we show that patterned Si nanowires can increase the Leidenfrost temperature while maintaining a minimum droplet evaporation lifetime. In particular, it is observed that the Leidenfrost point is reached when the phase-change time scale become dominant compared to the wicking time scale. Furthermore, it is observed that the extended region at the minimum droplet evaporation lifetime is attributed to the cyclic droplet jumping that controls the heat transfer process. These results could be important for enhancing the cooling performance and the safety margins of high thermal heat flux applications (e.g., heat exchangers and nuclear reactors). A super nano-wicking surface will allow maximizing the cooling in the transition boiling region due to the lift-off process and suppressing the Leidenfrost phenomenon even at higher temperatures.

See [supplementary material](#) for the details of the experiments and fabrication process.

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