Influence of surface topography in the boiling mechanisms

A.S. Moita*, E. Teodori, A.L.N. Moreira

In+, Dep. Mechanical Engineering, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

A R T I C L E   I N F O

Article history:
Received 15 May 2012
Received in revised form 25 August 2014
Accepted 5 November 2014
Available online 4 December 2014

Keywords:
Surface topography
Micro-textured surfaces
Pool boiling
Heat transfer
Bubble dynamics

A B S T R A C T

The present paper addresses the qualitative and quantitative analysis of the pool boiling heat transfer over micro-structured surfaces. The surfaces are made from silicon chips, in the context of pool boiling heat transfer enhancement of immersion liquid cooling schemes for electronic components. The first part of the analysis deals with the effect of the liquid properties. Then the effect of surface micro-structuring is discussed, covering different configurations, from cavities to pillars being the latter used to infer on the potential profit of a fin-like configuration. The use of rough surfaces to enhance pool boiling mainly stands on the arguments that the surface roughness will increase the liquid–solid contact area, thus enhancing the convection heat transfer coefficient and will promote the generation of nucleation sites. However, one should not disregard bubble dynamics. Indeed, the results show a strong effect of bubble dynamics and particularly of the interaction mechanisms in the overall cooling performance of the pair liquid–surface. The inaccurate control of these mechanisms leads to the formation of large bubbles and strong vertical and horizontal coalescence effects promote the very fast formation of a vapor blanket, which causes a steep decrease of the heat transfer coefficient. This effect can be strong enough to prevail over the benefit of increasing the contact area by roughening the surface. For the micro-patterns used in the present work, the results evidence that one can reasonably determine guiding pattern characteristics over micro-structured surfaces. The surfaces are made from silicon chips, in the context of pool boiling

1. Introduction

Novel cooling systems for high heat flux devices are required in industries such as transportation, microelectronics, solid–state lighting and manufacturing. Challenges arising from smaller chips, high performance microprocessors, higher operating frequencies in the electronic industry and brighter optical devices are leading to thermal loads as high as 100 W/cm², as reported for instance by Mudawar (2006). This is a well-known problem, which concerns the researchers for some years (e.g. Simons, 1987). However, consistent solutions have not been found yet, although the International Technology Roadmap for Semiconductors – ITRS points out the continuous trend of increasing power to be dissipated into very small areas. Among the various strategies that have been explored within the last decade to replace the conventional air natural, forced, mixed convection systems, an increasingly popular solution is directly immersing the components to cool in inert, dielectric liquids. In line with this, pool boiling is a very attractive solution, as it takes advantage of the latent heat of evaporation. Moreover, having no mechanical pumps, pool boiling hardware is less complex, easier to seal and free of pumped-induced fluid pulsation, which are present in many alternative approaches. The main set back is that dielectric liquids have lower values of thermal properties such as the specific heat and the latent heat of evaporation, when compared with other more common and inexpensive liquids, such as water. This is clearly shown in Table 1, which compares the thermo-physical properties of several refrigerant and dielectric

* Corresponding author. Tel.: +351 21 841 78 76; fax: +351 21 841 6956.
E-mail address: anamoita@dem.ist.utl.pt (A.S. Moita).

http://dx.doi.org/10.1016/j.ijheatfluidflow.2014.11.003
0142-727X/© 2014 Elsevier Inc. All rights reserved.
liquids with those of water. Here \( \rho \) stands for the specific mass, \( \mu \) for the dynamic viscosity and \( \sigma_l \) for the surface tension. \( T_{sat} \) is the saturation temperature, \( C_p \) is the specific heat, \( k \) is the thermal conductivity and \( h_{fg} \) is the latent heat of evaporation. The subscripts \( l \) and \( v \) represent the liquid and the vapor phases, respectively.

On the other hand, the cooling system will be more effective if the phase change of the liquid occurs closer to the working temperature of the chips. The high saturation temperature of the water (\( T_{sat} = 100 ^\circ C \)) does not satisfy this condition which can easily be achieved by most of dielectrics liquids (e.g. for HFE7000, \( T_{sat} = 34 ^\circ C \) and for HFE7100, \( T_{sat} = 61 ^\circ C \)). So, the cooling performance of the systems using dielectric liquids must be consistently enhanced, ensuring that the profits of a high efficiency of these systems overcomes the disadvantages of using expensive liquids with lower thermo-physical properties.

One of the most used arguments to enhance pool boiling is alter surface topography to increase the liquid/solid contact area and promote the appearance of active nucleation sites within the heterogeneous nucleation process, as reported in the earlier studies of Dorty and Foust (1955), Kurhara and Myers (1960), Hsu and Schmidt (1961) and Marto and Rohsenow (1966). It is worth mentioning that many of these studies, even recently reported (e.g. Ahn et al., 2010) make use of surfaces with stochastic roughness, sometimes associated to an ambiguous definition of the topographical characteristics. This strongly contributes to a non-consensual conclusion among the studies reported in the literature. This problem has been recently highlighted by Kothoff and Gorenflo (2009), Luke (2009), McHale and Garimella (2010) and Moita and Moreira (2012), who showed that any functional correlation can be derived to describe bubble dynamics (e.g. bubble departure diameter), based on the averaged quantities such as the mean roughness \( R_s \), the average peak-to-valley roughness \( R_d \) or the maximum roughness \( R_m \) which must be used to characterize stochastic roughness, since these quantities do not give enough representative information about the topography of the surface (e.g. the size of the rough peaks or cavities, or on the distance between them). Even before these questions have been raised, a number of studies have already dealt with the enhancement of boiling heat transfer, making use of regular surface micro-and-nanostructures, (e.g. Jo et al., 2011; Zao et al., 2011; Betz et al., 2013). In some cases, these micro-structures were manufactured directly on a silicon chip or on a simulated chip (e.g. Klein and Westwater, 1971). Among these studies, one may refer the work of Anderson and Mudawar (1989), who showed that the surfaces with microgrooves and square microstuds are highly effective in enhancing the nucleate boiling heat transfer coefficient in FC-72 and increasing critical heat flux. This enhancement is mainly due to an increase of the liquid–solid contact area. However, these surfaces exacerbated an incipience problem commonly encountered with low contact angle liquids: these liquids have a tendency to penetrate deep inside surface cavities, requiring unusually high levels of superheat to initiate the boiling process. Honda et al. (2002), Wei and Honda (2003) and Wei et al. (2005, 2007) performed a series of experimental studies on pool boiling enhancement using micro-pin-fins (10–50 \( \mu m \) in thickness and 60–200 \( \mu m \) in height) which were fabricated by dry etching. From the boiling incipience to the critical heat flux, the micro-pin-finned surfaces caused a sharp increase in the heat flux with increasing wall superheat. The increase of critical heat flux could be higher than twice that of a smooth surface. However, when dealing with regular patterns, other discrepancies occur, which are related to the optimum size and critical spacing between the cavities, the pillars or the fins. For instance, Klein and Westwater (1971) recommend a horizontal spacing of 1.6 mm, while Mudawar and Anderson (1989) identified a non-interference gap of 0.6 mm between pinfins. These values agree with the recommendations by Hiroto et al. (1985), mostly because these authors recommend a wide range of “optimum” horizontal spaces, ranging between 0.28 mm and 2.0 mm. Even so, there is no agreement when one compares these recommendations with those reported for instance by Bergles et al. (1995), which range between 0.4 mm and 1.0 mm. Yeh (1997) and by Guglielmini et al. (1999, 2001) sustain such discrepancies on the lack of full knowledge of pool boiling fundamentals (an extensive literature review on this subject is reported by Poniewski and Thome (2008)). Besides this strong argument, one should also refer that specific values for the optimization of pool boiling were determined experimentally for particular patterns and under specific working conditions. Hence, a more systematic approach is needed to relate the physics of the phenomena with the patterns, to determine a more general process to find the optimum patterns for heat transfer enhancement in pool boiling. Also, attention must be given to the way the surface topography is altered since in many situations both surface topography and wettability are varied, so that it is difficult to distinguish between the role of each factor. Despite the relation between surface topography, wettability and boiling has been debated since Fritz (1935), only recently, few authors have focused on systematic studies in which surface chemistry is modified while keeping the surface smooth (e.g. Bourdon et al., 2012, 2013).

A larger number of active nucleation sites are expected to be obtained by “rougheing” the surface, which should promote the bulk convection induced by bubble detachment and contributes to increase the heat that is removed by liquid vaporization. However, altering the topography of the surface also promotes several interaction mechanisms between nucleation sites, which may enhance or actually inhibit it, so that the negative effects of such interaction may actually overcome the potential advantages. Pioneering work of Chekanov (1977), Judd and Lavadis (1980), Judd (1988), Judd and Chopra (1993) and Zhang and Shoji (2003), emphasized the importance of these mechanisms in the overall efficiency of pool boiling heat transfer. More recently, Nimkar et al. (2006) and Yu et al. (2006) suggested that these mechanisms are the basic explanation for the different cooling performances of pool boiling over micro-textured surfaces, although any consensual conclusion was derived from different studies. This involves a deeper study of such mechanisms and of their relation with surface topography.

### Table 1
Thermo-physical properties of different dielectric fluids and water. Source: Arik (2001). \( T_{sat} \) – saturation temperature of the liquid; \( \rho \) – specific mass; \( \mu \) – dynamic viscosity; \( C_p \) – specific heat; \( k \) – thermal conductivity; \( h_{fg} \) – latent heat of evaporation; \( \sigma_l \) – surface tension of the liquid; \( P_c \) – critical pressure. The subscripts \( l \) and \( v \) represent the liquid and the vapor phases, respectively.

<table>
<thead>
<tr>
<th>Property</th>
<th>FC-72</th>
<th>HFE7000</th>
<th>HFE7100</th>
<th>Ethanol</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{sat} ) (°C)</td>
<td>56</td>
<td>34</td>
<td>61</td>
<td>78.4</td>
<td>100</td>
</tr>
<tr>
<td>( \rho ) (kg m(^{-3}))</td>
<td>1623</td>
<td>1374.7</td>
<td>1500</td>
<td>736.4</td>
<td>957.8</td>
</tr>
<tr>
<td>( \mu ) (mN s/m(^2))</td>
<td>12.7</td>
<td>4.01</td>
<td>9.6</td>
<td>1.647</td>
<td>0.596</td>
</tr>
<tr>
<td>( \mu ) (mN s/m(^2))</td>
<td>0.457</td>
<td>0.3437</td>
<td>0.61</td>
<td>0.448</td>
<td>0.279</td>
</tr>
<tr>
<td>( C_p ) (kJ/kg K)</td>
<td>1097.8</td>
<td>1352.5</td>
<td>1180</td>
<td>3185</td>
<td>4217</td>
</tr>
<tr>
<td>( k ) (W/m K)</td>
<td>0.052</td>
<td>0.07</td>
<td>0.07</td>
<td>0.165</td>
<td>0.68</td>
</tr>
<tr>
<td>( h_{fg} ) (kJ/kg)</td>
<td>84.97</td>
<td>142</td>
<td>125.6</td>
<td>849.9</td>
<td>2257</td>
</tr>
<tr>
<td>( \sigma_l ) (N/m) \times 10(^3)</td>
<td>8.4</td>
<td>12.4</td>
<td>14</td>
<td>17</td>
<td>58</td>
</tr>
</tbody>
</table>

### 2. Relation between bubble dynamics and surface topography
Following the pioneering work of Nukiyama (1934) and Drew and Mueller (1937), numerous studies have been devoted to understand pool boiling heat transfer. Several systematic approaches were followed to identify the most relevant system variables which can affect the boiling process such as:

---

• Surface micro-geometry (e.g. Cory and Fout, 1955; Berenson, 1962; Bier et al., 1979; McHale and Garimella, 2010).
• Wettability (e.g. Phan et al., 2009a,b).
• Thermo-physical properties of the heating surface (e.g. Golovin et al., 1964; Grigor’ev et al., 1973; Tolubinskiy et al., 1974).
• System pressure (e.g. Kim et al., 2007).
• Heater size (e.g. Lienhard et al., 1973; Park and Bergles, 1988; Kwark et al., 2010).
• Liquid level (e.g. Kutepov et al., 1977; Tolubinskiy, 1980; Pioro, 1997).

A detailed review on this topic can be found, for instance in Dhir (1998) and in Pioro et al. (2004).

Experimental work was closely followed by theoretical and semi-analytical models to describe nucleation and bubble formation (e.g. Fritz, 1935; Bankoff, 1958; Cole, 1967; Lorenz et al., 1974; Stefan, 1992; Wang and Dhir, 1993) volume (e.g. Mizukami, 1977; Forest, 1982; Nishio, 1985), to predict the heat flux transferred in the process (e.g. Rohsenhow) or even to predict the critical heat flux - CHF (e.g. Zuber, 1959; Kandlikar, 2001; Chu et al., 2012). Indeed it is known that for many industrial applications, including the cooling of microelectronic components, the research interest is focused on the nucleate boiling regime, until the critical heat flux. Since in most of those systems, the heat flux \( q' \) is the independent variable, as soon as the critical heat flux is reached, the temperature of the system may exceed abruptly the burnout values. Therefore, many researchers point to enhance the heat transfer coefficient within the nucleate boiling region, while trying to increase the critical heat flux and delay the onset of the critical heat flux conditions, as much as possible (e.g. Arik, 2001). However, enhancing these quantities by altering the surface topography has three main difficulties:

(i) the determination of the heat transferred in pool boiling over modified surfaces is still strongly based on semi-empirical approaches (e.g. Jabardo et al., 2004);

(ii) despite it is widely accepted that boiling incipience is related to the formation of a bubble following a relation between wall superheat and radius, \( R_c \), of a nucleating cavity:

\[
T_W - T_{at} = \frac{2\sigma_{lq} r_k}{R_c h_f \rho_f} K
\]

there is still no agreement on the accurate definition of the condition for \( K \), which is related to the angle of the cavity and in turn, to the definition of the role of wettability. Such role is not yet completely defined either when describing bubble growth and departure.

(iii) As introduced above, altering the surface topography will affect the interaction mechanisms in a way that must be well established, (e.g. Tedori et al., 2013).

In fact, very little is known about these interaction mechanisms. Chekanov (1977) and later Judd and Lavdas (1980), Judd (1988), Judd and Chopra (1993), produced two artificial nucleation sites differently spaced. These authors identified diverse regions of interaction among nucleation sites, as a function of the dimensionless cavity spacing \( S/D_d \), where \( S \) is the distance between two cavity centers (thus the distance among nucleation sites) and \( D_d \) is the mean bubble departure diameter. However, once again, there is no agreement between the conclusions reported within the different studies, probably due to some differences in the experimental conditions, but also due to the lack of consistency in the identification of the various mechanisms which may occur. Later, Zhang and Shoji (2003) attempted to solve this issue and proposed an alternative set of interaction regions, also as a function of \( S/D_d \), trying to associate the differences in the regions with the dominance of one of three crucial effects, namely hydrodynamic interaction between bubbles, thermal interaction between nucleation sites and horizontal and declining bubble coalescence. Based on this criterion, Zhang and Shoji (2003) distinguish four intensity regions:

(i) for \( (S/D_d > 3) \) none of the three interactions can be observed, so the two artificial cavities are independent and behave like a single cavity; (ii) for \( (2 < S/D_d < 3) \) hydrodynamic interaction between bubbles is the predominant mechanism; (iii) for \( (1.5 < S/D_d < 2) \) both hydrodynamic and thermal interaction between the bubbles will affect their dynamic behavior; (iv) for \( (S/D_d < 1.5) \) all the three effects have an influence on the behavior of the process, overall contributing to an increased bubble departure frequency. The main limitation of these important contributions is probably the very restricted number of cavities which turns difficult any extrapolation to the rough surfaces used in practical applications, which have numerous cavities. Afterwards, recent research such as the work (cited above) of Nimkar et al. (2006) and Yu et al. (2006) present much valuable experimental quantifications on the effect of the spacing between arrays of cavities with different shapes, and speculate the possible influence of the interaction mechanisms, but do not propose further modifications to the categorization of Zhang and Shoji (2003), or try to expand such categorization to the significantly larger number of cavities that they used, when compared to Zhang and Shoji (2003).

This brief review highlights the great effort that has been put within the last decade to improve the heat transfer coefficient for pool boiling, altering the surface topography. The lack of understanding of the effect of the micro-patterns in the nucleation mechanisms and in the bubble dynamics is one of the main obstacles to achieve this goal. The tremendous variety of topographical patterns adds complexity to the problem. So, a more systematic approach must be taken, in which the role of boiling dynamics and of the interaction mechanisms may be relevant.

In line with this, the present work addresses a detailed study on the pool boiling over micro-patterned surfaces. The surfaces are made of silicon wafers, in the context of the application to cooling of microelectronic devices, as provided in Section 1. Different liquids are used, namely the dielectric liquids HFE7000 and HFE7100, ethanol and water, to account for the influence of the liquid properties as well as to infer on the additional effects of wettability in the observed phenomena. Heat flux measurements are gathered with qualitative and quantitative information obtained from high-speed visualization and image post-processing (e.g. boiling morphology, bubble departure diameter, bubble departure frequency and active nucleation site density) to describe the boiling mechanisms.

The discussion of the results introduces first the effect of the liquid properties on bubble dynamics. Then the effect of surface micro-structuring is discussed, covering different configurations, from cavities to pillars. The latter is used to infer on the potential take profit of a fin-like configuration.

3. Experimental apparatus and methodologies

The experimental set-up is composed by a heating element (copper block heated by cartridge heaters), the pool boiling test section, a high-speed camera (Phantom v4.2 from Vision Research Inc., with 512 × 512 pixels@2100 fps and a maximum frame rate of 90 kfps) and a DAQ acquisition system. Fig. 1 shows a global view of the copper support. The whole heating block is insulated by epoxy. This was the set-up used to accommodate the micro-textured surfaces made of silicon wafers, which have an area of 100 mm² and a thickness of 380 μm. This configuration allowed achieving heat fluxes up to 250 W/cm².
It is worth mentioning that despite the enlarged shape of the copper block, the heat flux was only evaluated based on the measurements of type K thermocouples located within the boiling area (100 mm²). The remaining area was insulated and the thermocouples positioned there served only to control how the heating was occurring, so their readings are not used to compute the heat flux. There is a thermocouple reading the temperature of the silicon chip. The signals of the thermocouples are sampled with a National Instruments DAQ board plus a BNC2120 and amplified with a gain of 300 before processing. The acquisition frequency is 100 Hz and the temperature is monitored for 20 s after reaching a stable condition (constant temperature variation which does not exceed ±0.5 °C). The liquid is pre-heated and degassed in a pre-chamber. The refilling and the entire measurement processes are automatically controlled using a number of valves. The system responds based on the information provided by a pressure transducer (OMEGA DYNE Inc.). The control system reacts to pressure variations in the order of 5 mbar. Heaters disposed on the sides of the pool boiling chamber are controlled by a PID controller to assure that the heat remains inside the chamber at saturation temperature.

The heat losses evaluated for this configuration are in the order of 18% (in extreme conditions and very high heat fluxes estimation of the heat losses could reach up to 37% in the worst case. Hence such conditions were not used). Regardless of the non-negligible heat losses (18%), the obtained boiling curves can be comparable to those reported in the literature, as it will be discussed in Section 3.2.1.

The heat losses were estimated for various imposed heat fluxes. Here, the environmental losses are evaluated considering the copper and the epoxy as a composed wall. Thermal properties were gathered from the literature and the conductivity of the epoxy (1.4 W/m K) was provided by the manufacturer. Heat losses are evaluated for natural convection with air at $T_{\text{air}} = 23$ °C. Hence, from the energy balance to the heating block, the term $(\rho C \text{Volume})_{\text{block}} \partial T/\partial t$ must equal the imposed heat transfer minus the heat removed by natural convection, as explained, for instance in Incropera and DeWitt (1995). Since the natural convective term also depends on the surface temperature, the effective heat flux is determined iteratively, obtaining convergence after 2 iterations. The uncertainties of the imposed heat flux can be determined, as further explained in Section 3.2.3. The power dissipated inside the heating block can be estimated, as $\partial T/\partial t$ can be determined from measured values. Hence, the differences obtained between the experimental estimation and the energy balance can be attributed to heat losses.

### 3.1. Characterization of the test surfaces

The surfaces used here are made from a silicon wafer, which are micro-structured with regular patterns.

For a more systematic approach, a first set of tests is introduced using patterns of square micro-cavities, with fixed size length $a = 52 \mu m$ and fixed depth $h_\text{R} = 20 \mu m$. The distance between the centers of the cavities, $S$ ranges between 300 $\mu m < S < 1200 \mu m$. Afterwards regular patterns composed by quadrangular pillars were also tested to infer on the potential profit of a fin-like configuration. The pillars of side $a$ and height $h_\text{R}$ are apart within a distance $b$. The fundamental wavelength is $\lambda_{\text{R}}$, as defined in Fig. 2a. The patterns are printed on the silicon wafer by lithography and processed by plasma etching. To reach higher pillars/deeper cavities, the wafer surfaces were coated with aluminum, before the lithography. So, besides plasma etching, wet chemical etching is required for the aluminum coating.

The micro-patterns are controlled to have known, precise values, using a Dektak 3 profilometer (Veeco) with a vertical resolution of 200 Å. An example of a roughness profile is depicted in Fig. 2b. Finally, the surfaces are checked by SEM/EDS analysis. Heterogeneity of the patterns was found to be lower than 3%.

The wettability of the surfaces was also characterized, based on the static contact angle $\theta$, following the approach presented by many authors (e.g. Phan et al., 2009a,b). The contact angles are measured at room temperatures, inside a thermostatted ambient chamber (Ramé-Hart Inc., USA, model 100-07-00), using the Sessile Drop Method. Images of the deposited droplet are recorded with a JVC Color T-1079 video camera.
mounted on a Wild M3Z microscope, with a magnification of 40 times. An average value is considered for each pair liquid–surface which is determined from at least five measurements taken at different regions of the surface. The time evolution of the average contact angles is obtained by curve fitting and the final values are determined by extrapolation. The detailed measurement procedure has been described in previous works (e.g. Moita and Moreira, 2012).

It is worth noting that this is the apparent wetting angle of liquid droplets deposited over the surfaces and not the local angle defined at the departure gas bubbles. For the surfaces roughened with the micro-patterns, the value of this angle allows performing an estimation of the wetting regime. According to the classical theory, if the liquid completely penetrates within the pillars – the so-called homogeneous regime, the contact angle $\theta$ is theoretically determined by Wenzel’s equation (1936). Alternatively, in the heterogeneous wetting, the liquid cannot completely penetrate within the pillars creating air pockets, which may facilitate the triggering of the heterogeneous boiling. Within this regime $\theta$ is predicted by Cassie and Baxter’s theory (1944). The heterogeneous wetting is naturally more likely to occur with liquids like water, with larger surface tension and therefore larger $\theta$, when compared with liquids such as ethanol and HFE, which completely wet the surface ($\theta \approx 0^\circ$). In the present work, the apparent contact angle measurements and a visual inspection of the droplet deposition using the Wild M3Z microscope leads to the indication of the occurrence of the homogeneous wetting regime, for all the pairs liquid–surface used. However, very small deformations, of the order of 1–5 $\mu$m seem to be generated at the base of the micro-pillars, as a result of the structuring process. The vapor entrapment that may arise from there is globally insignificant in terms of altering the boundary conditions of the problem (concerning the contact area), but can endorse the heterogeneous boiling process. This may be so since, making use of Wang and Dhir (1993) relation to predict the critical radius for the triggering of the bubble formation (Eq. (1)) and using $T_W - T_{sat}$ based on the experimental measurements, which are further presented in Section 4, the critical radius is of the order of a few microns (between 1 and 5 $\mu$m, depending on the fluid properties). So, knowing that the bases of the pillars are working as active nucleation sites, the patterns used to discuss the results in Section 4 were selected from a wider range. These patterns were chosen as they evidence the effect of each of the parameters identified in Fig. 2 on boiling dynamics.

The characteristics of the surfaces micro-patterned with cavities are summarized in Table 2, while the surfaces micro-patterned with pillars are described in Table 3.

Ageing of the surfaces was periodically verified (in each measuring round) by checking the surface topography with the profilometer and by measuring the surface contact angles. Similar procedure was suggested by Bernardin and Mudawar (1996) and followed for instance in Moita and Moreira (2007).

### Table 2
Main range of the topographical characteristics of the surfaces micro-patterned with cavities. $\theta$ is the average static contact angle measured with water at room temperature. $\theta \approx 0^\circ$ for all the surfaces in contact with ethanol and HFE7000/7100.

<table>
<thead>
<tr>
<th>Material wafer</th>
<th>Reference</th>
<th>$\theta$ (°)</th>
<th>$h_R$ (µm)</th>
<th>$\lambda_e$ (µm)</th>
<th>$R_a$ (µm)</th>
<th>$S$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon wafer</td>
<td>Smooth</td>
<td>$\approx 0$</td>
<td>$\approx 0$</td>
<td>$\approx 0$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$C_1$</td>
<td>52</td>
<td>20</td>
<td>304</td>
<td>90.0</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$C_2$</td>
<td>52</td>
<td>20</td>
<td>400</td>
<td>91.5</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$C_3$</td>
<td>52</td>
<td>20</td>
<td>464</td>
<td>71.5</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$C_4$</td>
<td>52</td>
<td>20</td>
<td>626</td>
<td>86.5</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$C_5$</td>
<td>52</td>
<td>20</td>
<td>700</td>
<td>95.0</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$C_6$</td>
<td>52</td>
<td>20</td>
<td>800</td>
<td>60.5</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$C_7$</td>
<td>52</td>
<td>20</td>
<td>1200</td>
<td>66.3</td>
<td>$-$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

The contact angles were evaluated with water. Measurements performed with the profilometer did not show significant variations in the surface topography. Variations measured in the contact angles were within the expected range due to hysteresis and any significant wettability changes were detected. With the other liquids, i.e. ethanol and HFE7000/7100, the contact angles are very close to zero so any variations in the wettability were also measured. Based on this periodic characterization one can argue that any significant ageing effects are present in the results obtained here.

### Table 3
Summary of the main range of the topographical characteristics (as defined in Fig. 10) used in the customized surfaces micro-patterned with pillars. The table also depicts the static contact angles measured at room temperatures with water. For ethanol and HFE7000/7100 $\theta \approx 0^\circ$ for all the surfaces.

<table>
<thead>
<tr>
<th>Material wafer</th>
<th>Reference</th>
<th>$\theta$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon wafer</td>
<td>Smooth</td>
<td>$-$</td>
</tr>
<tr>
<td>$C_1$</td>
<td>85</td>
<td>1.2</td>
</tr>
<tr>
<td>$C_2$</td>
<td>282</td>
<td>7.6</td>
</tr>
<tr>
<td>$C_3$</td>
<td>127</td>
<td>12.8</td>
</tr>
</tbody>
</table>

The boiling curve is reconstructed for the various liquids and surfaces, based on the visualization of the boiling morphology and on the heat flux calculations. A detailed analysis of the boiling mechanisms (e.g. bubble departure diameter and frequency, nucleation site densities) is performed by extensive image post-processing. The dynamic bubble boiling mechanisms are then associated with the heat flux measurements, to infer on the liquid/patterned surface configuration which optimizes the heat flux, while keeping the boiling mechanisms under beneficial activity.

#### 3.2. Methodology

Qualitative and quantitative characterization of the various pool boiling regimes is achieved by combining high-speed visualization with temperature measurements and heat transfer calculations. Different liquids are used, namely water, ethanol and two dielectric fluids, HFE7000 and HFE7100. The thermo-physical properties of the liquids used in the present study were already introduced in Table 1.

The boiling curve is reconstructed for the various liquids and surfaces, based on the visualization of the boiling morphology and on the heat flux calculations. A detailed analysis of the boiling mechanisms (e.g. bubble departure diameter and frequency, nucleation site densities) is performed by extensive image post-processing. The dynamic bubble boiling mechanisms are then associated with the heat flux measurements, to infer on the liquid/patterned surface configuration which optimizes the heat flux, while keeping the boiling mechanisms under beneficial activity.

#### 3.2.1. Pool boiling curves

Each boiling curve presented for every liquid and every heating surface used here are averaged from four experiments, as illustrated in Fig. 3. Hysteresis effects were also inferred by increasing
To validate the experimental results, the bubble departure frequency was measured for every nucleation site identified in the frame. The bubble departure frequency can usually be estimated by two methods: (i) determining the temporal difference between the beginning of two successive bubble formation events at the same nucleation site or (ii) determining the time elapsed between apparent departure events. The second method was used in the present work. So, the bubble departure events are counted for a defined time interval. Then, the bubble departure frequency is calculated as the ratio between the number of events and the time elapsed between the first and the last departure events. The departure frequency is assessed, for each test condition, for at least five nucleation sites. The final value of the bubble departure frequency is the average between the frequencies of each nucleation site.

For each test condition, the bubble departure frequency is evaluated based on extensive image post-processing of 300–1060 frames.

3.2.2.2. Bubble departure frequency. The bubble departure frequency can usually be estimated by two methods: (i) determining the temporal difference between the beginning of two successive bubble formation events at the same nucleation site or (ii) determining the time elapsed between apparent departure events. The second method was used in the present work. So, the bubble departure events are counted for a defined time interval. Then, the bubble departure frequency is calculated as the ratio between the number of events and the time elapsed between the first and the last departure events. The departure frequency is assessed, for each test condition, for at least five nucleation sites. The final value of the bubble departure frequency is the average between the frequencies of each nucleation site.

For each test condition, the bubble departure frequency is evaluated based on extensive image post-processing of 300–1060 frames.

3.2.2.3. Nucleation site density. The evaluation of the nucleation site density requires a huge effort, since any software/code are available to identify the number of nucleation sites on the surfaces, so it has to be done by visual inspection of the frames, (following previous work such as McHale and Garimella, 2010) which introduces an uncertainty associated to the subjective criterion of the observer. In order to lessen this uncertainty, at least ten frames are chosen in different times during every single experiment. The final nucleation site density is then an average of the ten evaluated values.

3.2.3. Measurement uncertainties

The main uncertainties of the quantities related to the heat transfer measurements are summarized in Table 4. The uncertainty in the temperature measurements is assessed according to Abernethy et al. (1985). The maximum combined uncertainty is the maximum value of uncertainty obtained for all the pairs liquid/surface tested. Table 5 summarizes the uncertainties of the main quantities related to the bubble parameters.

The thermal resistance at the contact of the surface, thermocouple and thermal paste was estimated theoretically, considering a 1D conduction heat flux and overestimating the thickness of the thermal paste to be up to 500 μm. Then, for different imposed fluxes, the temperature difference between upper and lower walls were determined by high-speed infrared thermography, using a Onca-MWIR-InSb thermographic camera, with a temporal resolution of 2 ms, at resolution of 320 × 256 pixels (maximum frame rate of 7600 fps at 32 × 32 pixels) and a sensitivity of 17 mK. The maximum thermal resistance was of the order of 0.02 cm² K/W.

4. Results

4.1. Effect of the properties of the liquids for boiling on surfaces with micro-cavities

This section introduces the effect of the liquid properties on the boiling curves and bubble dynamics, focusing on the role bubble dynamics and of the interaction mechanisms. The results obtained with surfaces micro-structured with cavities are already introduced here, given that these surfaces can be used to better control the appearance of the nucleation sites, thus it is easier to understand the evolution of nucleation sites density as a function of
the heat flux. However, the analysis will mainly emphasize the effect of the liquid properties. Then the use of surfaces micro-patterned with pillars is discussed in Section 4.2.

Following Moita et al. (2012), Fig. 5 relates the heat flux with bubble dynamics, namely bubble departure diameter, nucleation sites density and bubble departure frequency, for the pool boiling of water, ethanol and HFE over micro-patterned surfaces with different spacing between the cavities, S.

The figure shows that nucleation sites density naturally increases with the number of cavities (i.e. for surfaces with smaller S). For relatively low heat fluxes (5–10 W/cm²), HFE and for HFE and between 10 and 20 W/cm² for water), the increase of the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a sudden increase of the number of active nucleation sites and of the bubble departure frequency. The large value of the latent heat of evaporation of water delays the beginning of the boiling process, so water boiling has the lowest nucleation sites density, which increases very gradually with the heat flux and with the number of cavities (for surfaces with smaller S). On the other hand, the lowest value of $h_{fg}$ of HFE allows the fast activation of a large number of nucleation sites, even at low heat fluxes. Naturally, the higher degree of metastability that is required to trigger boiling incipience for water also leads to higher degrees of superheating and the heat flux naturally activates the cavities, leading to a S.
and face can actually allow improving the pool boiling heat transfer, as long as one can optimize the patterns to act on the coalescence, when using liquids with high \( h_{fg} \) and \( \sigma \). In this case, \( S \) is directly

Fig. 5. Nucleation characteristics of water, ethanol and HFE on the silicon wafer surfaces patterned with micro-cavities: (a) bubble departure diameter, (b) nucleation sites density, and (c) bubble departure frequency.

Fig. 6. Coalescence factor versus heat flux for pool boiling over the silicon wafer surfaces patterned with micro-cavities for: (a) water, (b) ethanol, and (c) HFE7000.
acting on the coalescence mechanisms which occur close to the surface and so should be related to the force balance describing the bubble detachment, as proposed by Fritz (1935) and followed by many other researchers to scale bubble departure diameters: 
\[ L_c = (\sigma_{lv} g (\rho_l - \rho_g))^\frac{1}{2} \]. A representation of the ratio between the average heat transfer coefficient for the surfaces structured with cavities with the heat transfer coefficient for the smooth surface, as a function of the distance \( S \), made dimensionless with \( L_c \) was proposed in Teodori et al. (2013) and clearly shows that for these surfaces, for liquids with lower values of \( \rho_l \) and \( \sigma_{lw} \), micro-patterning leads to and improvement of the pool boiling heat transfer, while for water, this improvement is relative and is strongly dependent on interaction mechanisms and particularly on coalescence.

### 4.2. Effect of micro-patterns composed by pillars

For this part of the work, surfaces micro-patterned with pillars are tested, to infer on additional cooling benefits of fin-like patterns. Contrarily to what occurs at the surfaces with cavities, in this case it is much more difficult to detect the nucleation sites. From extensive observation, it was detected that the nucleation sites are always observed at the base of the surface, in the corner of the pillars. The use of rough surfaces to enhance pool boiling mainly stands on the arguments that the surface roughness will increase the liquid–solid contact area, thus enhancing the convection heat transfer coefficient and will promote the generation of nucleation sites. Regarding the first premise, an increase of the ratio between the true and wetted area should enhance the heat transfer. However, following the discussion in the previous section one should not disregard the bubble dynamics and particularly the interaction mechanisms, which could easily lead to “dangerous” situations where the vapor formation near the surface would rapidly deteriorate the heat transfer efficacy. The use of different patterns is discussed here to infer on the effect of the various characteristic parameters \( (a, h_g, b) \) on the in-balance between the relative importance of bubble dynamic modifications, promoted by altering the surface topography, with the effective increase of the true to the wetted area also obtained by structuring the surface, in the overall heat transfer efficacy, namely in the boiling curve and in the heat transfer coefficients. Since the surfaces used in this work have well defined patterns, it is possible to specify a roughness factor, which gives the ratio of the true to the wetted area, \( r_f = 1 + \left[ 4 h_g \sigma_{lw} (b + a)^2 \right] \), thus providing an indication of the actual increase of the liquid solid contact area. \( r_f = 1.005 \) for surface \( S_1 \), \( r_f = 1.02 \) for surface \( S_2 \) and \( r_f = 1.07 \) for surface \( S_3 \). An increase of \( r_f \) and therefore of the wetted area is usually associated to higher heat transfer coefficients and higher CHF, as reported for instance by Chu et al. (2012), although these authors only show significant improvement of the heat transfer for much higher values of \( r_f \) between 3 and 6. Naturally that this improvement may also be related to capillary pumping and to additional liquid circulation. In the present paper, the values of \( r_f \) are much lower than those reported by Chu et al. (2012), however, there is still a significant increase of the roughness factor from surface \( S_1 \) to the other two surfaces. Then, a milder increase of this factor occurs between surfaces \( S_2 \) and \( S_3 \), so bubble dynamics should play the determinant role. Following the previous analysis and considering a homogeneous wetting behavior for all the pairs liquid–surface, the larger contrast expected is between the well distributed boiling of HFE and the boiling of water, which is the liquid with the highest surface tension, for which the interaction mechanisms are more relevant. Fig. 7 depicts the boiling morphology of water over the various surfaces and evidences already the strong coalescence, leading to a violent boiling, when compared to that of HFE (Fig. 8).

The figures also show that the surface micro-patterns clearly alter the boiling morphology for water. The micro-pattern in \( S_2 \) is the one promoting a more distributed boiling all over the surface, with less interaction among nucleation sites. This partial control of the bubble dynamics allows delaying the degradation of the heat transfer coefficient to occur only for higher values of the heat flux, which is worth reminding to be caused by strong coalescence that lead to the formation of vapor blankets.

The evaluation of the bubble dynamic characteristics confirms these qualitative observations. Fig. 9a, which depicts the bubble departure diameter as a function of the Jakob number,
Ja = ρCp(Tw - Tsat) / (ρhffg), shows that the boiling over surface S2, despite having almost the same nucleation sites as surface S3 (Fig. 9b), is characterized by less interaction among nucleation sites and less coalescence, generates the smallest bubble departure diameters (which are of the order of the spacing between the pillars, up to quite large heat fluxes) when compared with all the other surfaces. This may be so since, as aforementioned, the bubbles usually form at the base of the pillars, thus the distance among them and their dimensions will influence the nucleation sites interaction. A direct comparison with the study of Chekanov (1977), Judd and Lavdas (1980), Judd (1988), Judd and Chopra (1993) or Zhang and Shoji (2003) is not possible because the geometry of the current micro-patterns does not allow to determine accurately the ratio S/D. A close estimative would get that all the surfaces allow the interaction between nucleation sites (which is correct looking at the relative size of the pillars, when compared to the bubbles departure diameter), but for surface S2 the horizontal coalescence is less intense, due to the larger spacing between the pillars.

Vertical coalescence still occurs because the area of the pillars is of the order of the size of the radius of the bubbles which depart at each side of the pillars, but the spacing between them precludes horizontal coalescence and delays the formation of the vapor blanket, while allowing some liquid to flow between the pillars. The schematic representation reported in Fig. 10 helps to understand this mechanism.

Fig. 8. HFE boiling morphology on the silicon wafer surfaces patterned with micro-pillars: (a) S2 (rf = 1.02) Ja = 9.62, (b) S3 (rf = 1.07), Ja = 11.45, (c) S2 (rf = 1.02) Ja = 47.37, and (d) S3 (rf = 1.07), Ja = 42.51. The physical width of each image is approximately 8 mm.

Fig. 9. Bubble dynamic characteristics of water boiling over the silicon wafer surfaces patterned with micro-pillars. (a) Bubble departure diameter, and (b) nucleation sites density.

Fig. 10. Interaction among adjacent nucleation sites due to the spacing among pillars: (a) largest and more distant pillars avoiding coalescence, and (b) thinner and nearer pillars promoting coalescence.
As expected, the smallest number of active nucleation sites is observed in the boiling over the smooth surface. The partial control of the interaction mechanisms promoted by surface $S_2$ results in the highest heat fluxes and heat transfer coefficients, despite this is not the surface providing the largest $r_f$ (Fig. 11a). It clearly lessens the degradation of the heat transfer coefficient, characterized by the decrease of $h$, which is noticeably observed at higher heat fluxes, for all the other surfaces, in Fig. 11b.

In summary, unless the micro-structure assures a significant increase of the liquid–solid contact area, the interaction mechanisms can indeed be overcome by the deterioration of the heat transfer coefficient resulting from uncontrolled interaction mechanisms. Therefore, the design of an optimum micro-pattern must account for the accurate parameters allowing the control of these mechanisms. In the present work, the best control was obtained with surface $S_2$. Although this is the surface with the largest pillars and the highest spacing among them, this trend cannot be extrapolated as an optimum pattern, since that was out of scope of the present paper and requires further research.

The interaction among nucleation sites and coalescence effects are much smaller for HFE (Fig. 8), so in this case it is quite clear that the number of active nucleation sites is larger for surface $S_2$, which
further contributes to its good performance. However, the interaction mechanisms are still not negligible, particularly at high fluxes and, also in this case, $S_2$ is the best performing surface. So, for low values of heat fluxes, qualitative analysis suggests that both $S_2$ and $S_3$ still provide a very uniform boiling. However, increasing the heat flux, a much stronger coalescence is observed for the surface $S_3$, for which the smaller spacing between the pillars is promoting coalescence.

This trend is confirmed by quantitative analysis, depicted in Fig. 12a and b, which show the bubble departure diameter and the nucleation site density for HFE, for increasing $f_a$.

Given that the effect of the interaction mechanisms is not so significant for liquids with smaller $\sigma_{lv}$, when compared to an increase of the contact area, the slightly larger value of $r_f$ of surface $S_3$ still allows to obtain high heat fluxes and heat transfer coefficients when compared to $S_2$ (Fig. 13a), for lower superheating. However, as the heat flux increases, the stronger coalescence effects in surface $S_3$ becomes more evident, both in the boiling curves and in the heat transfer coefficient, as depicted in Fig. 13b. So, one may argue that $S_2$ is, once again the surface allowing the best performance.

The use of HFE is mainly related to its dielectric properties, which enable it to be used as coolant in microelectronic devices. Despite its lower thermo-physical properties, the balance between a reasonable control of the interaction mechanisms with the increase of the liquid–solid contact area provided by the use of the structured surfaces, $S_2$ allows a substantial increase of the heat transfer coefficient of nearly 8 times, when compared to that obtained with the smooth surface. Better results can be expected for a more careful and optimized design of the micro-patterns.

The overall improvement in the pool boiling heat transfer of HFE achieved with surface $S_2$ actually allowed it to overcome the performance of water for high heat fluxes, since the control of the interaction mechanisms for water is still not enough to prevent the steep degradation of the heat transfer coefficient, as depicted in Fig. 14a and b.

The worst performance of surface $S_3$ in controlling the interaction mechanisms is highlighted in Fig. 15a and b. In this case, the uncontrollable interaction mechanisms actually lead to such a steep degradation of the heat transfer coefficients for water boiling that they drop below those of HFE.

The measurements performed here do not evidence a substantial advantage of using pillar structures concerning an additional capillary pumping. To achieve this, specific optimization of the surface patterning should be required, for which the measurement techniques used so far must be also complemented with diagnostic techniques to characterize the flow around the pillars, following the work started in Teodori et al. (2013). However, it is clear that the control of the nucleation sites and of the interaction mechanisms is vital in any patterning optimization, as these mechanisms may easily become dominant and overcome any beneficial effect of surface patterning.

5. Final remarks

The present work considers the detailed analysis of the heat transfer and bubble dynamics in pool boiling of liquids over smooth and micro-structured surfaces, in the context of an application to the cooling of microelectronic components. In this kind
of application, the use of dielectric fluids is mandatory, although their thermal–physical properties such as the specific heat, thermal conductivity or latent heat of evaporation are quite low. A steep decrease of the heat transfer coefficient. This effect can be particularly of the interaction mechanisms in the overall cooling performance of the pair liquid–surface, which is particularly relevant for liquids with large values of surface tension. The inaccurate control of these mechanisms may easily become dominant causing a steep decrease of the heat transfer coefficient. This effect can be strong enough to prevail over the benefit of increasing the contact area by roughening the surface. For the patterns used here, one can reasonably determine guiding geometric characteristics of the pattern to evaluate the intensity of the interaction mechanisms and take out the most of the patterning to enhance pool boiling heat transfer, when using micro-cavities, it is far more difficult to control the appearance of active nucleation sites and of the interaction mechanisms when dealing with the patterns based on micro-pillars.

Despite it was not possible to clearly evidence of a pin-fin effect or of an additional cooling effect due to liquid circulation between the pillars, the results show a significant increase of the heat transfer coefficient of about 10 times for water and 8 times for the dielectric fluid, in comparison to the smooth surface, when the micro-patterning based on pillars is used.

Acknowledgments

The authors are grateful to Fundação para a Ciência e a Tecnologia (FCT) for partially financing the research under the framework of projects PTD/EME-MFE/109933/2009 and RECI/EMS-SIS/0147/2012. The authors also acknowledge FCT for supporting E. Teodoro with a PhD fellowship (Ref: SFRH/BD/88102/2012) and A.S. Moita with a Post-Doc Grant (Ref: SFRH/BPD/63788/2009).

References


