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BYPASSING FILM BOILING STATE FOR MAINTAINING HIGH BOILING HEAT TRANSFER EFFICIENCY BY DIELECTROPHORETIC EFFECT

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ABSTRACT

Over the last few decades, steady improvements in manufacturing processes of microprocessors have been the primary reason for a substantial reduction in the size of electronic devices. The resulting increase in heat density generation leads to an immense demand for compact and compatible heat management systems capable of effectively dissipating the heat generated from these devices. Two-phases heat transferring technique is one of the most efficient ways to dissipate heat from the hot surface. This technique is also known as boiling heat transferring, in which heat is rapidly carried away from the hot surface by latent heat of the boiling bubble to the free liquid surface. However, it comes along with an operation limit, called critical heat flux, at which the bubble nucleate rate is fast enough to form a steady film of vapor upon the surface and subsequently prevents the heat from transfer to the free surface. Due to the low thermal conductivity of the vapor film, heat flux through the surface is dramatically reduced, causing the overheat of the surface and the surface or the device will be eventually reached the burn-out state. Beyond this limit, boiling transfers from nucleate boiling to film boiling. In this study, we introduce a novel approach to completely avoid this limit of film boiling by using dielectrophoretic effect. We experimentally conduct several boiling experiments with various levels of voltage applied to the dielectrophoretic chips. We observe that dielectrophoretic effect not only increases the critical heat flux but also completely bypass film boiling state with almost no limit of superheat. The enhancement of heat flux can be up to 200% at the film boiling state with the current max voltage applied in the experiment.

1. INTRODUCTION

Over the last few decades, steady improvements in manufacturing processes of microprocessors have been the primary reason for a substantial reduction in the size of electronic devices [1]. The resulting increase in heat density generation leads to an immense demand for compact and compatible heat management systems capable of effectively dissipating the heat generated from these devices. Therefore, a variety of heat transfer enhancement techniques have been developed in the literature, utilizing either single-phase or multiphase fluids. Cooling of electronic chips using two-phase heat transfer [2–3] can be considered as the state-of-the-art solution for heat transfer enhancement. In most applications using two-phase heat transfer technique, the heat is taken away from the hot surface by the evaporation of bulk cooling liquid adjacent to the surface. The optimum rate of heat dissipation from the surface is determined by the specific latent heat of evaporation during nucleate boiling, which is usually much higher than the specific sensible heat capacity of conduction via vapour film boiling. Therefore, film boiling state is the cause of rapidly overheat and burn-out of substrate surface and subsequently leads to an irreversible destruction of the electronic devices.

In this work, we introduce a novel approach to completely bypass film boiling state to maintain high boiling heat transfer efficiency by using dielectrophoretic effect. This not only allows to extend the maximum heat generating from the electronic device to almost unlimited value, but also maintain a thermally safe environment for the devices. We first experimentally investigate the effect of dielectrophoretic on heat flux during the whole boiling process, including convective boiling, nucleate boiling and film boiling. Our measurements indicate that it is possible to control heat flux or even bypass

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the rapidly dropping of heat flux during film boiling by simply increasing the electrical potential supplied to the dielectrophoretic chip. Our data analysis will be further carried out to evaluate the potential needed to surpass the effect of film boiling as well as its bypassing mechanism.

2. METHODOLOGY

In our experimental setup (Fig. 1a), the dielectric liquid (HFE-7000) is kept inside a glass tube of diameter 12 mm × 100 mm in length. The space surrounding the glass tube is thermally insulated by a 10 mm layer of sponge foam rubber. The glass tube is open at the top, allowing vapor to reach a condenser, which is a copper coil with cool water circulated through. A pressure relief valve is installed on the top cap of the glass tube to prevent over pressure inside the tube and to keep the vapor medium at atmospheric pressure. The substrate is made of a 500 µm thick sapphire wafer and is glued to a copper rod of diameter 12 mm using thermal silicon paste with a high thermal conductivity of 5 W/(mK) (S606C, T-global Technology). The copper rod is embedded with a 400 W cartridge heater (HLG2403, Hakko) and type-K thermocouples with the tip diameter of 1 mm; the setting temperature T_{set} is controlled by a 0.1 s response time PID controller (E5CC, Omron), which is connected to a thermocouple and cartridge heater. Three Pt100 thermal sensors (T_1, T_2, and T_3, Fig. 1a) are inserted at evenly spaced positions along the axis of the copper rod to measure the net heat flux and the surface temperature. Here, the thermal contact resistance between the thermal sensors and the copper rod is accounted for via the following external calibration process. The copper rod is placed in a temperature calibration bath and heated to different stable set temperatures. The thermal sensors are used to obtain stable temperatures and then calibrated against the stable set temperatures indicated by the calibration bath. The heat flux q through the copper block is calculated as $q = -k_c T_x$, where k_c is the thermal conductivity of copper, and the temperature gradient T_x is calculated using the temperatures measured by the thermal sensors in the copper block and the distance Δx_{c_1} between them: $T_x = (3T_3 - 4T_2 + T_1)/(2\Delta x_{c_1})$. As a result, the surface temperature is estimated by extrapolation as $T = T_3 - qR$, where $R = \Delta x_{c_2}/k_c + \Delta x_p/k_p + \Delta x_s/k_s$ is the total thermal insulance from the third thermal sensor (T_3) to the top surface. Here, k_p, k_s, Δx_p, and Δx_s are the thermal conductivities and thicknesses of the thermal paste layer and the sapphire substrate, respectively. Finally, the surface superheat, ΔT, is calculated by subtracting surface temperature T with boiling point T_b of the working liquid (HFE-7000, 56 ºC), $\Delta T = T - T_b$.

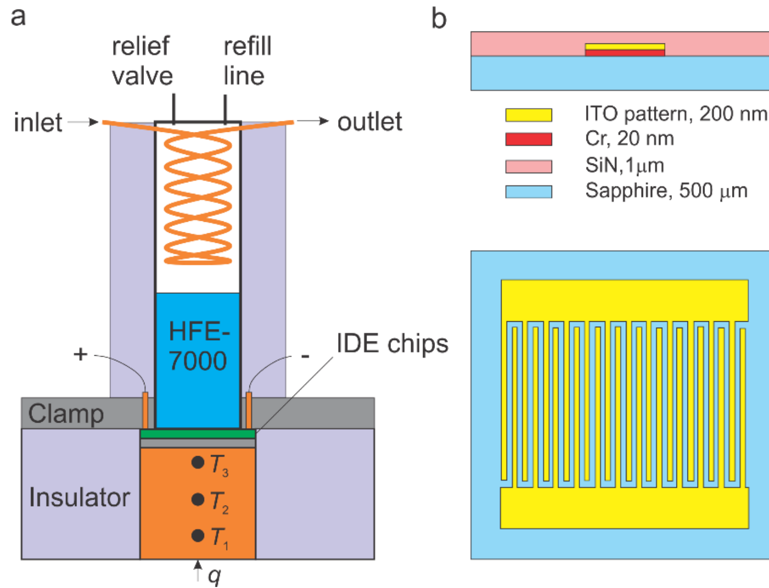

Figure 1: (a) Schematic (not to scale) of the experimental setup. (b) The design of dielectrophoretic substrate includes an ITO pattern of interdigitated electrode, an insulation layer of silicon nitride and the sapphire base.

The electrophoretic substrate is consisted of a 500 μm sapphire base, a 20 nm of chromium as connecting layer and a 200 nm of indium tin oxide (ITO) as interdigitated electrodes. On top of the substrate, a 1 μm layer of silicon nitride (SiN) is coated on the whole surface as an electrical insulation layer (Fig. 1b), except the two electrode connection pads. The two electrode connection pads are exposed to the top surface and are connected outside by a pair of gold-coated pins attached on the claim. Each experiment starts by setting the voltage supplied to the dielectrophoretic substrate. The substrate is then gradually heated to reach a target surface superheat temperature T_{set}. We then calculate the corresponding heat flux q and measure the surface superheat ΔT. The experiment will then be repeated with six levels of supplied voltage (0 V, 900 V, 1100 V, 1300 V, 1500 V and 1700 V). The experimental uncertainty is obtained by repeating the experiment three times for each experimental condition.

3. RESULTS AND DISCUSSIONS

In Fig. 2, we plot the boiling curve for different levels of voltage supplied to the dielectrophoretic substrate together with that case of no voltage applied. We observe that while dielectrophoretic can enhance boiling heat transfer efficiency at all three boiling zones along the boiling curve (conductive, nucleate and film boiling zone), its effect becomes the most significant at film boiling zone. Interestingly, that effect is so strong that it can indeed bypass film boiling at high supplied voltage ($U \geq 900$ V). The heat flux measurement on the 1700 V boiling curve shows that its heat flux value reduces just a minor amount before it is increasing again at higher surface superheat (ΔT = 75 K). The local minimum heat flux value of the 1700 V boiling curve (q = 30.14 W/cm^2) can be seen to be close to the critical heat flux value of 0 V boiling curve (q = 34.3 W/cm^2). By observing the snapshot of boiling process with U = 0 V and 1700 V at ΔT = 100 K (Fig. 2b), it is obviously that the greatly enhancement in heat transfer efficiency is the result of different boiling types: film boiling and nucleate boiling. In other words, the trigger of dielectrophoretic effect during film boiling makes it transfer from film boiling to nucleate boiling, which in turn has a much higher heat removal rate.

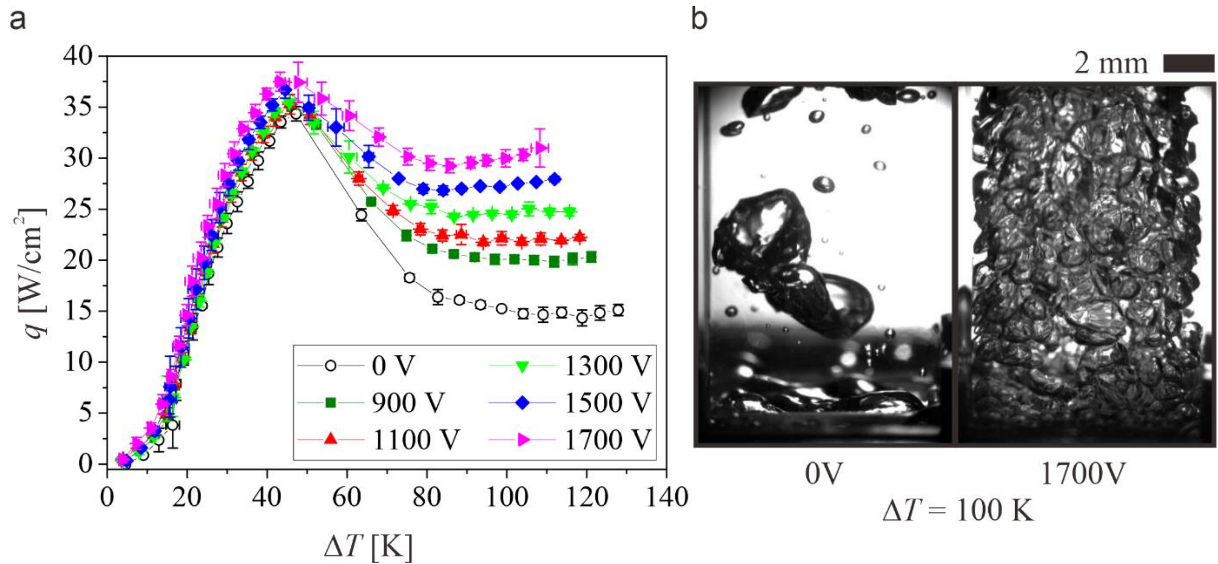

Figure 2: (a) Boiling curve of different voltage levels, the obvious enhancement of boiling heat transfer efficiency can be observed mostly in film boiling state. (b) Snapshots showing the transferring from film boiling to nucleate boiling when the voltage U = 1700 V is supplied at ΔT = 100 K.

Since the main mechanism of heat transfer enhancement of dielectrophoretic effect is to switch from low heat transfer efficient filming boiling to nucleate boiling, the effect is clearly amplified at film boiling state. We now look at the boiling efficiency at critical heat flux (CHF) and at film boiling state with T_{set} = 127 K, which is the highest limit superheat for our current setup. In Fig. 3a and 3b, we show the net change in superheat ($\Delta T_U - \Delta T_{U=0}$) and heat flux ($q_U - q_{U=0}$) while applying voltage to

dielectrophoretic chip at both superheat cases (at CHF and T_{set} = 127 K). For surface superheat, the activation of the electrophoretic chip helps to reduce the superheat temperature up to 3 K at CHF state and 20 K at film boiling state. On the other hand, heat flux through the surface also increases 3 W/cm^2 at CHF state and 15 W/cm^2 at film boiling state, which is equivalent to the enhancement of 10% and 200% in heat flux respectively compared with the case without voltage. In both cases, the enhancement of heat transfer efficiency is observed to be amplified greatly in film boiling zone whereas it shows least improvement close to CHF. Since the boiling happens at CHF is already violently and has a very high heat removal rate with high bubble density and bubble departure frequency, there is not much improvement for dielectrophoretic effect. When the boiling state moves from nucleate boiling at CHF to film boiling, the role of dielectrophoretic effect is much more significant. In detail, dielectrophoretic effect provides a net pulling pressure underneath the vapor film and therefore suck the liquid back to touch hot surface. In another word, the dielectrophoretic effect greatly encourages the rewetting ability of the surface, contributes to the disruption of vapor film, which subsequently lead to nucleated boiling again with much higher heat transfer efficiency.

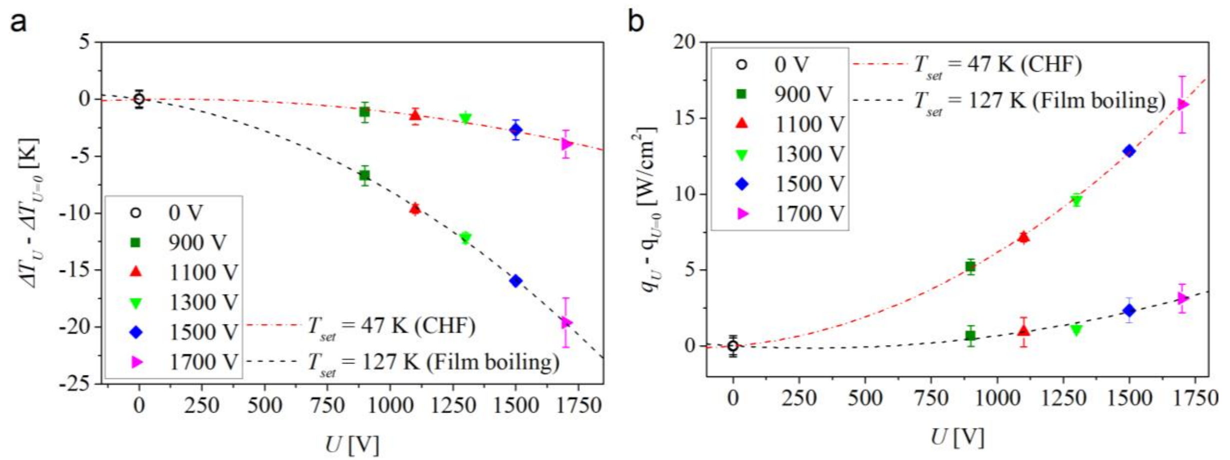

Figure 3: (a) Net change in superheat ($\Delta T_U - \Delta T_{U=0}$) and (b) Net change in heat flux ($q_U - q_{U=0}$) while applying voltage to dielectrophoretic chip at two superheat cases at CHF and T_{set} = 127 K.

To identify the critical voltage value U that is needed for switching smoothly between film boiling and nucleate boiling without dramatically drop of heat flux (as observed in Fig. 2a, with U = 900 V), we need to refer to the mechanism of how electrophoretic affect the boiling state. Vo and Tran [4] have concluded that the electrical field gradient between two consecutive electrodes creates a pulling pressure p_e onto the dipole liquid hovering at a distance of h_0 above it with a certain penetration depth d_p: $p_e \sim U^3\ e^{2h_0/d_p}$. Since film boiling also create a vapor pressure between the upper liquid and the substrate, these two types of pressure would be balanced to find the critical value of voltage needed to be applied to the dielectrophoretic substrate. The detail balance between these two types of pressure needs to have a deeper experiment and analysis and currently be out of the scope of our current study. However, in Fig. 3a and b, we can observe that the rate of changing net superheat and heat flux increases largely along with voltage applied. As shown in Fig. 3, the relation of boiling efficiency (represented by net superheat and heat flux) and dielectrophoretic effect (voltage applied) is nonlinear. The vapor pressure causes by evaporation of liquid on hot surface can be estimate by heat flux through that surface as $p_v \sim q$, and the boiling heat flux at nucleate boiling state can be calculated using Rohsenow model [5] as $q \sim g \Delta T^3$, where g is a constant depend on the boiling liquid properties. On the other hand, the vapor film thickness h_0 also depends on heat flux q through the surface. Assuming that relation is proportional ($h_0 \sim q$) and expand the expression e^{2h_0/d_p} by Taylor series to the third order, the dielectrophoretic yields $p_e \sim U^3(q^3 + o(4))$. Now, the balancing between p_e and p_v yields $U^3 q^3 \sim g \Delta T^3 \rightarrow U \sim \Delta T/q \sim 1/h$,where h is the heat transfer coefficient of boiling heat transfer.

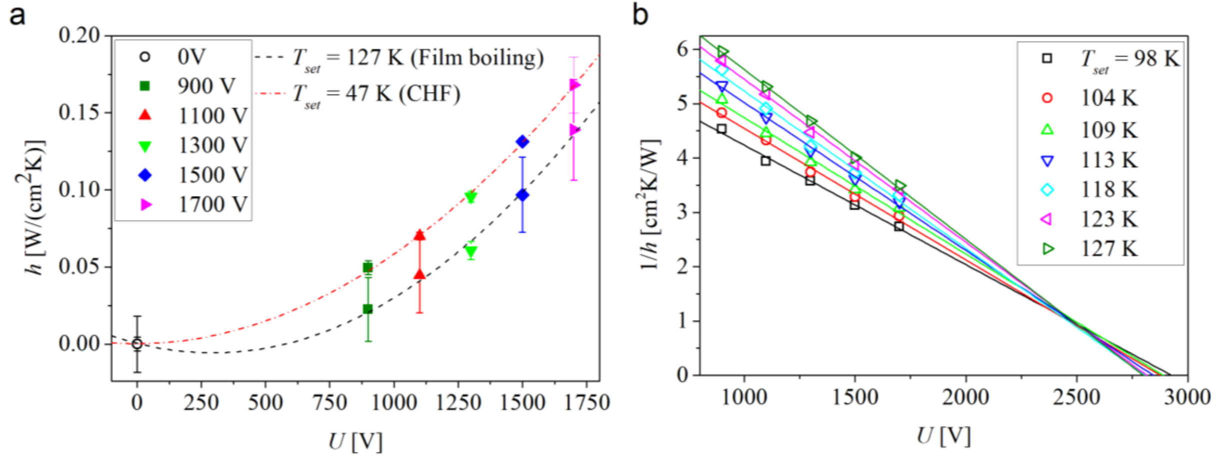

Figure 4: (a) Net change of heat transfer coefficient, h, at two superheat cases (at CHF and T_{set} = 127 K) with various level of applied voltage U. (b) For each superheat starting from T_{set} = 98 K to the maximum T_{set} = 127 K, the value of $1/h$ shows a linear relationship with applied voltage U.

The above analysis allows to dynamically control the heat transfer coefficient h of a boiling state by adjusting the voltage U applied to the dielectrophoretic chip. In Fig. 4a, we plot the heat transfer coefficient h along with applied voltage U at CHF and at film boiling state. The result again suggests a nonlinear relation between them, while h increases faster at higher U. To validate the analysis, in Fig. 4b, we plot the $1/h$ along with U for all superheat heat starting from T_{set} = 98 K to the maximum T_{set} = 127 K. The superheat of 98 K is chosen since the boiling process is steady beyond that temperature and to avoid any disturbances caused by the transition boiling zone. Interestingly, the data points fit well with linear correlation for all value of superheat (Fig. 4b). These results allow us to dynamically control and predict the heat transfer coefficient h when applying dielectrophoretic in pool boiling through applied voltage U. This also suggest that there is almost no limit to increase heat transfer efficiency with dielectrophoretic effect, although there is a value of U beyond that the effect of dielectrophoretic seem to be saturated (~3000 V).

4. CONCLUSIONS

In summary, we have experimentally introduced a novel and robust method for enhancing heat transfer by bypassing the film boing state using dielectrophoretic effect. The mechanism of enhancing heat transfer efficiency will be explained by balancing between pulling pressure caused by dielectrophoretic effect and the vapor pressure created during film boiling. The results from this work show that sufficient potential voltage from dielectrophoretic effect can be used to significantly enhance the rate of heat transfer from heated substrates even at film boiling state. In this study, the current enhancement rate of heat flux is up to 200% and can be even higher with larger applied voltage. These results have a very good potential in practical as an extra safety measurement to avoid burnout state of electronic chips and devices. Moreover, the dynamically control of heat transfer coefficient of boiling allow a flexible design for the future electronic chips and devices.

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