Experimental Thermal and Fluid Science 35 (2011) 825–831

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Evaporation and flow dynamics of thin, shear-driven liquid films in microgap channels

O.A. Kabov [a,b], D.V. Zaitsev [a,b], V.V. Cheverda [a,*], A. Bar-Cohen [c]

[a] Universite Libre de Bruxelles, Chimie-Physique EP-CP165/62, Microgravity Research Center, Avenue, F.D. Roosevelt 50, Bruxelles B-1050, Belgium
[b] Kutateladze Institute of Thermophysics, Siberian Branch of Russian Academy of Sciences, Lavrentyev 1, Novosibirsk 630090, Russia
[c] University of Maryland, Department of Mechanical Engineering, College Park, TherPES Laboratory, MD 20742, United States

ARTICLE INFO

Article history:
Received 21 March 2010
Received in revised form 29 July 2010
Accepted 4 August 2010
Available online 7 August 2010

Keywords:
Two-phase flow
Regimes
Heat transfer
Local heating
CHF

ABSTRACT

Thin and ultra-thin shear-driven liquid films in a narrow channel are a promising candidate for the thermal management of advanced semiconductor devices in earth and space applications. Such flows experience complex, and as yet poorly understood, two-phase flow phenomena requiring significant advances in fundamental research before they could be broadly applied. This paper focuses on the results obtained in experiments with locally heated shear-driven liquid films in a flat mini-channel. A detailed map of the flow sub-regimes in a shear-driven liquid film flow of water and FC-72 have been obtained for a 2 mm channel operating at room temperature. While the water film can be smooth under certain liquid/gas flow rates, the surface of an intensively evaporating film of FC-72 is always distorted by a pattern of waves and structures. It was found, that when heated the shear-driven liquid films are less likely to rupture than gravity-driven liquid films. For shear-driven water films the critical heat flux was found of up to 10 times higher than that for a falling film, which makes shear-driven films (annular or stratified two-phase flows) more suitable for cooling applications than falling liquid films.

1. Introduction

The Moore's law progression in semiconductor technology, including shrinking feature size, increasing transistor density, and faster circuit speeds, is leading to ever higher chip power dissipation and heat fluxes. Roadmap projections for the high-performance chip category suggest that the maximum chip power dissipation will exceed 300 W and the chip heat flux exceed 150 W/cm^2 within the next few years [1]. Moreover, in recent years, increasing performance demands have resulted in greater non-uniformity of on-chip power dissipation, creating localized, "hot spots," often exceeding 1 kW/cm^2 in heat flux, which can degrade the processor performance and reliability [2,3]. Similar developments are underway in microwave integrated circuits and power amplifier chips, with even higher localized heat fluxes. The application of conventional thermal packaging technology, developed to provide chip cooling for uniform, far more modest heat fluxes, to such chip designs results in poor and inefficient thermal management.

The forced flow of dielectric liquids, undergoing phase change while flowing in a narrow channel, is a promising candidate for the thermal management of advanced semiconductor devices in terrestrial and space applications [4]. Such channels may be created by the spacing between silicon ribs in a microchannel cooler, between stacked silicon chips in a three-dimensional logic, RF, or heterogeneous microsystem, narrowly-spaced organic or ceramic substrates, and between a chip and a non-silicon polymer cover in a microgap cooler [5].

These microgap configurations provide direct contact – and hence cooling – between a chemically-inert, dielectric liquid and the back surface of an active electronic component, thus eliminating the significant thermal resistance associated with a Thermal Interface Material (TIM) or the solid–solid contact resulting from the attachment of a microchannel cold-plate to the chip. While direct contact cooling is thermally very efficient, in such configurations, it is the poorly understood two-phase flow phenomena that establish the upper bound on the heat removal capability. Thus, prediction of the thermal characteristics and limits, as well as the development of strategies for performance enhancement, of microgap coolers, requires an in-depth understanding of the underlying thermo-physics of two-phase flow in narrow channels.

Two-phase flow in miniature channels is dominated by annular flow, with thin liquid films flowing along the walls and a vapor core in the center [4]. The behavior of such thin and ultra-thin (less than 10 μm) liquid films, driven by shear forces produced by the forced gas/vapor flow (as in annular [4–7] or stratified [8–12] flows), is at the heart of the thermal performance of such microgap coolers [13]. The present work will provide an overview of two-

* Corresponding author.
E-mail address: vcheverd@ulb.ac.be (V.V. Cheverda).

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doi:10.1016/j.expthermflusci.2010.08.001