Design and Testing of Microfabricated Electrostatic Fluid Accelerator

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Abstract:

The micro cooling industry requires novel cooling solutions to compensate for heat generated by increasingly component-dense electronic and MEMS devices. Rotary fan technology is unable to produce adequate fluid flow and is not readily scaleable. Electrostatic fluid acceleration (EFA) provides an energy efficient high performance alternative that has the potential to be manufactured directly into the electronics themselves. Proof of concept micro EFA devices were fabricated and tested for their operational I-V characteristics. Geometric optimizations were incorporated in design, and their effects demonstrated experimentally.

Introduction:

Rapidly shrinking electronics and MEMS devices generate heat from electrical resistance, mechanical friction, and even combustion processes. Existing thermal management solutions have inadequate heat removal and energy efficiency characteristics to meet industry needs.

Conventionally, heat dissipates away from a hot substrate through a thermally conductive heatsink. Fluid flow then removes this heat to the atmosphere. The traditional rotary fan fails to offer the performance and flexibility demanded by advanced thermal management applications. High speed moving parts produce unwanted vibration and noise and are difficult to scale down. Resulting cross sectional air velocity profiles are static and experience a dip in the center opposite the motor assembly.

Electrostatic fluid acceleration which ionizes and accelerates an atmospheric fluid in a desired flow pattern is a promising replacement for the removal, or fluid flow, stage in micro cooling. EFA technology has been around for some time, and has been investigated for use in air filtration, propulsion, humidification, propulsion, and audio speakers. For the cooling of microelectronic and MEMS devices, EFA offers several important advantages over the rotary fan: near laminar air profile with controllable velocities, simple solid-state electrode geometry which offers excellent design flexibility and ease of manufacture, low power consumption, large convective heat transfer, and the possibility to decrease the effective boundary layer at the solid fluid interface within an enclosed structure like a channel. The mechanisms of EFA action by corona discharge based ionization have been previously investigated and modeled with respect to electrostatic, fluid dynamic, and space charge effects [1]. Practical micro EFA devices were fabricated and tested for their operational voltage and current characteristics in the first ever foray into the development of an integrated, or on-chip, EFA device.

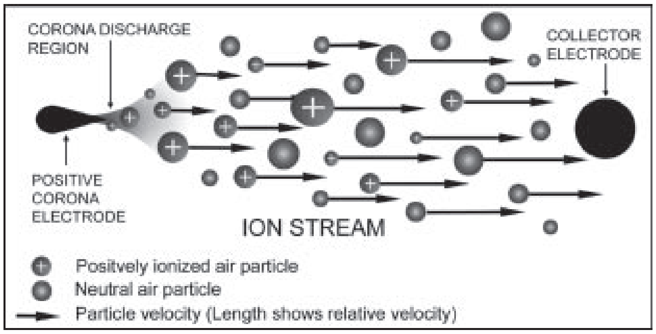

Figure 1: Ion wind from EFA operation.

Background:

The mechanism of EFA action is illustrated in Figure 1. Voltage is applied between a high tip curvature corona electrode and a low tip curvature collector electrode. High electric field intensity in the vicinity of the corona electrode ionizes air molecules. These ions are accelerated towards the collector, transferring kinetic energy to surrounding neutral molecules. The EFA has three regions of operation. At low levels of applied voltage, the EFA is cut-off and has zero current. At some onset voltage the EFA current begins to increase exponentially with applied voltage. The EFA operates between the onset voltage and the breakdown voltage, where dielectric breakdown occurs between the corona and collector electrodes, causing sparking between the electrodes and poor net fluid flux.

A wide range of different air velocities and voltage characteristics have been reported for different devices. The variables of import are the corona surface area, air gap size, and corona electrode curvature. Experiments at the macro and meso scale have investigated the variation of these parameters and what follows is the application of understood optimizations to micro devices.

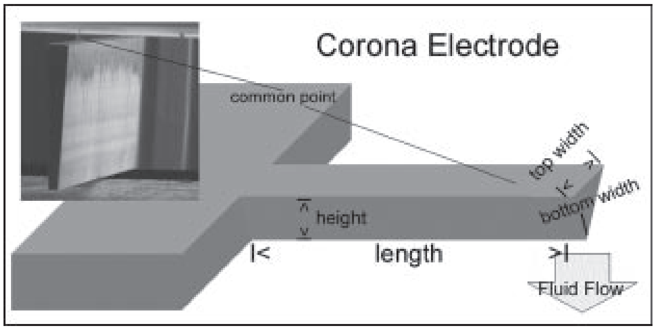

Figure 2: Corona electrode geometry and SEM image.

Procedure:

Devices were fabricated from bulk silicon using industry standard photolithographic techniques. Lowering the necessary onset voltage for EFA operation was the principle design goal. Figure 2 shows the geometry of the devices alongside an SEM image of an actual device. The wafers were etched using deep reactive ion etching (DRIE).

High curvature was desired at the very tip of the long cantilever on the underside of the wafer. The overall tip length serves to isolate the tips' electric field from that of the low curvature base. The negative sidewall tapering (top width > bottom width) was achieved by patterning large spacing around the cantilever for masking during the DRIE. Devices were fabricated with varying tip length, height, top width, and bottom width. Etch times were continually modified to establish reliable expectations of tip dimensions and curvature. Figure 3 shows a device with sharpening by RIE for high tip curvature.

Results:

The devices were tested to obtain current-voltage relationships for micro EFA device operation at known corona electrode to collector electrode orientations and separation distances. The devices were held at a distance above a semiconductive foam collector electrode by a micro-positioning x-z stage. SEM imaging was used before and after tests to ensure devices conformed to desired dimensions and did not change during operation or from breakdown effects.

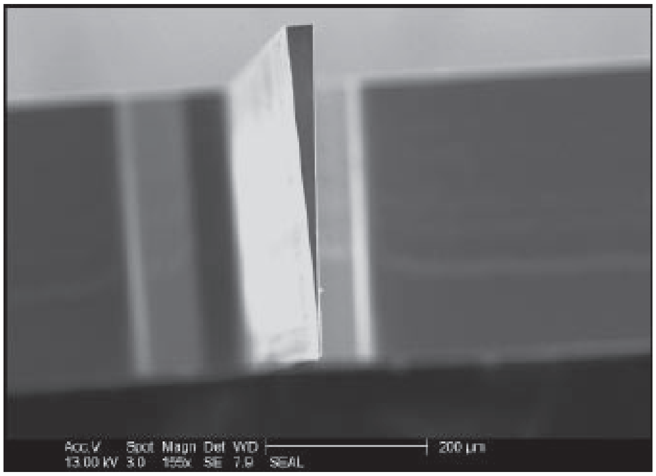

Figure 3: Ultra high tip curvature electrode.

Micro devices were tested to determine the dependency of onset and breakdown voltages on tip length as well as air gap size between electrodes. Positive voltage was applied to the Corona electrode and the collector was held at a lower voltage. Current data points were taken for a particular device geometry and air gap size throughout the cut-off and operational voltage range up until the expected point of breakdown or appearance of sparks. Figure 4 shows the effects of variations in air gap size on the operational voltage range of a 5 mm long tip. Operational voltage range increased along with the air gap size.

Experimental data, not shown here, indicates that onset voltage is lowered and operational range extended for devices with longer tips. This was observed via extensive testing of 3, 5, and 8 mm tip lengths. Preliminary tests indicated air velocities for some devices in excess of 2 m/s.

Future work includes further miniaturization and characterization of micro EFA devices moving towards a fully optimized single wafer on-chip solution.

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References:

[1] N. E. Jewell-Larsen, P. Q. Zhang, C. P. Hsu, I. A. Krichtafovitch, and A. V. Mamishev "Coupled-physics modeling of electrostatic fluid accelerators for forced convection cooling" IAA/ASME June 2006.

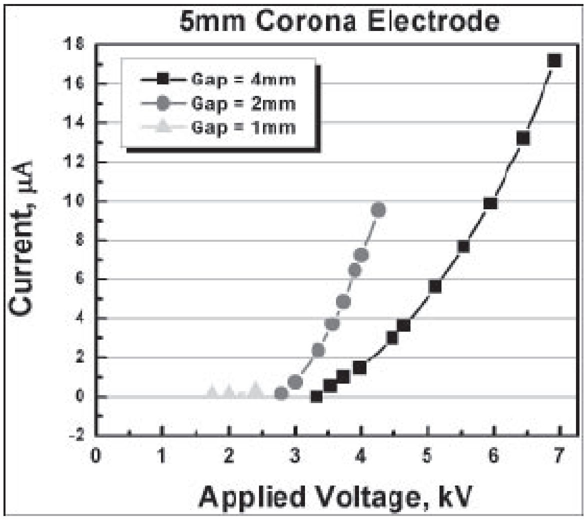

Figure 4. Current-voltage curves for EFA operation at various electrode separations.